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Strategic Petroleum Reserve (SPR) Creep-Closure Test on Sulphur Mines Cavern 6

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Abstract

This report presents a brief history of Sulphur Mines cavern 6, describes a creep-closure test, and gives the results of the test. At the test conditions from March 1984 through July 1985, the cavern produced an average of 73 barrels of brine per day. Finite element calculations using a laboratory-determined creep model and cavern geometry are compared with the field data.

Acknowledgments

We acknowledge the contributions of Steve Lowery, Boeing Petroleum Services, Inc., for coordinating the on-site activities and test support, and of Dave Tomasko, SNLA, for his support associated with thermal analysis and modeling.

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Strategic Petroleum Reserve (SPR) Creep-Closure Test on Sulphur Mines Cavern 6

Introduction

The development of mathematical models for predictions of cavern and well behavior must include predictions of closure caused by salt creep as a function of pressure and time. To obtain actual field data for model verification, we collected data from several wells and caverns including West Hackberry (WH) 11 and 112,' Sulphur Mines (SM) 6, all wells at Big Hill (BH), Bryan Mound (BM) 5, and Bayou Choctaw (BC) 18 and 20. These wells and caverns will be evaluated to determine the effects of cavern shape, depth, salt properties, temperature, and other variables. These data will provide the baseline to evaluate the performance of instrumentation under a long-term cavern monitoring plan. This report will describe the data collected from SM 6 and the analyses of these data.

History and Background

Wells 6X and 6Y were originally completed in 1955 as brine-producing wells. A sonar caliper survey conducted in 1975 for Pittsburgh Plate Glass (PPG) indicated a cavern volume of 4.37×10^6 bbl.[2]

The site has a commercial history dating back to 1868 when the Louisiana Petroleum and Coal Oil Company drilled its first oil exploration well. Subseqent exploration discovered large depcsits of high-quality sulphur in the caprock. After several attempts to mine the sulphur conventionally, Herman Frasch invented a method to recover the sulphur using pressurized hot water. Approximately 9,400,000 tons of sulphur were removed from the caprock, using the Frasch process. The removal of this vast amount of sulphur allowed the overlying caprock to collapse, causing subsidence at the surface. In addition to the sulphur production, oil and gas have been produced by Union Texas Petroleum Company from the flanks of the dome and from the caprock. PPG and Allied Chemical have active storage and brining operations in the dome. PPG produces brine from wells 14 and 15. Allied Chemical stores ethylene in wells 1 and 3.[3]

In 1977 the Department of Energy (DOE) acquired -640 acres for the SPR facility at SM from Allied Chemical. During 1977, Gulf Interstate Engineering Company undertook certification studies for each of the acquired caverns. These were the 2-4-5 gallery and caverns 6 and 7 (holes BW2 to 7 in Figure 1). All were found suitable for oil storage for five storage cycles.' Later, DOE determined that SM would be used for only one storage cycle. The storage potential in 1977 was estimated to be 24 million barrels.[3] The cavern and well locations are shown in Figure 1. The shape of cavern 6, as determined in 1981 by a sonar survey, is illustrated in Figure 2. The total volume was calculated to be 5.63×10^6 bbl.

A workover of well 6X (well BW6X in Figure 1) by Williams-Fenix & Sisson (W-F&S) in 1979 included installation of the 7-5/8-in production casing to a depth of 2505 ft.[4] A workover of well 6Y by W-F&S in 1979 included installation of the 7-in production casing to a depth of 2502 ft.[5] Reentry well 6Z was completed by W-F&S in 1979 and the 13-3/8-in production casing was installed to a depth of 2574 ft.[6] The configurations of the three wells after cavern testing was 'completed on July 6, 1981,[7] and prior to the beginning of oil fill in mid-July 1981 are shown in Figures 3, 4, and 5. The oil fill was initiated in mid-July 1981 and was completed by July 1982. In 1983, there were minor withdrawal/refill cycles and the cavern was filled and returned to a stable condition by November 1983. To our knowledge, there has been no oil movement into or out of the cavern between November 1983 and July 1985. The oil volume in cavern 6, as quoted by Boeing Petroleum Services, Inc. (BPSI) in June 1985, is 6.79×10^6 bbl, with a total cavern volume of 7.00×10^6 bbl. The oil-brine interface depth and the cavern's oil temperature histories are shown in Table 1. A linear regression of the well 6Z interface locations indicates a downward interface movement of -3 ft/yr. This movement is due primarily to salt creep and to the oil temperature increase.

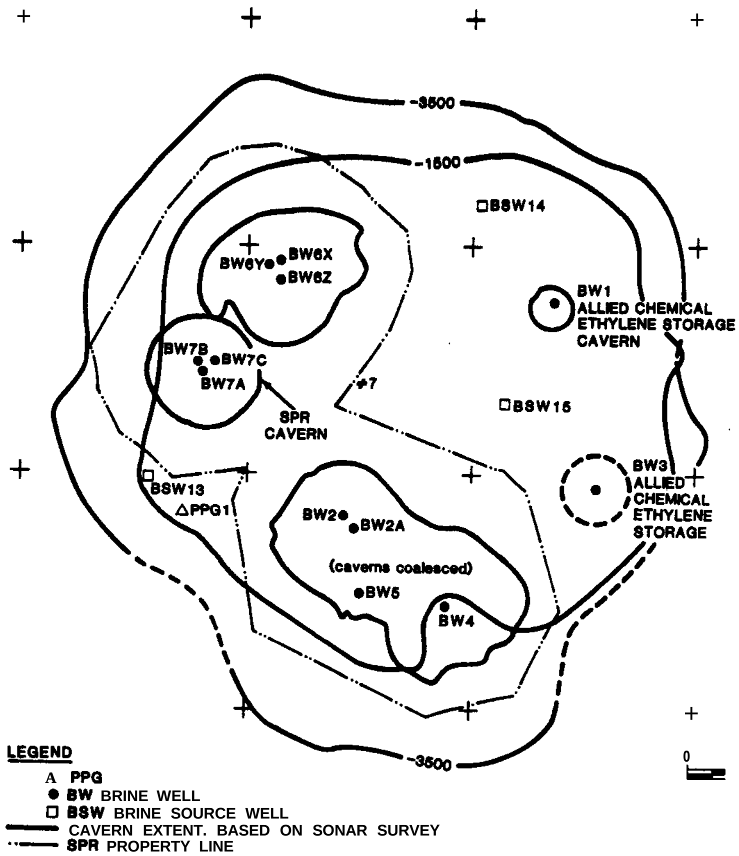

Figure 1. Sulphur Mines Site Layout

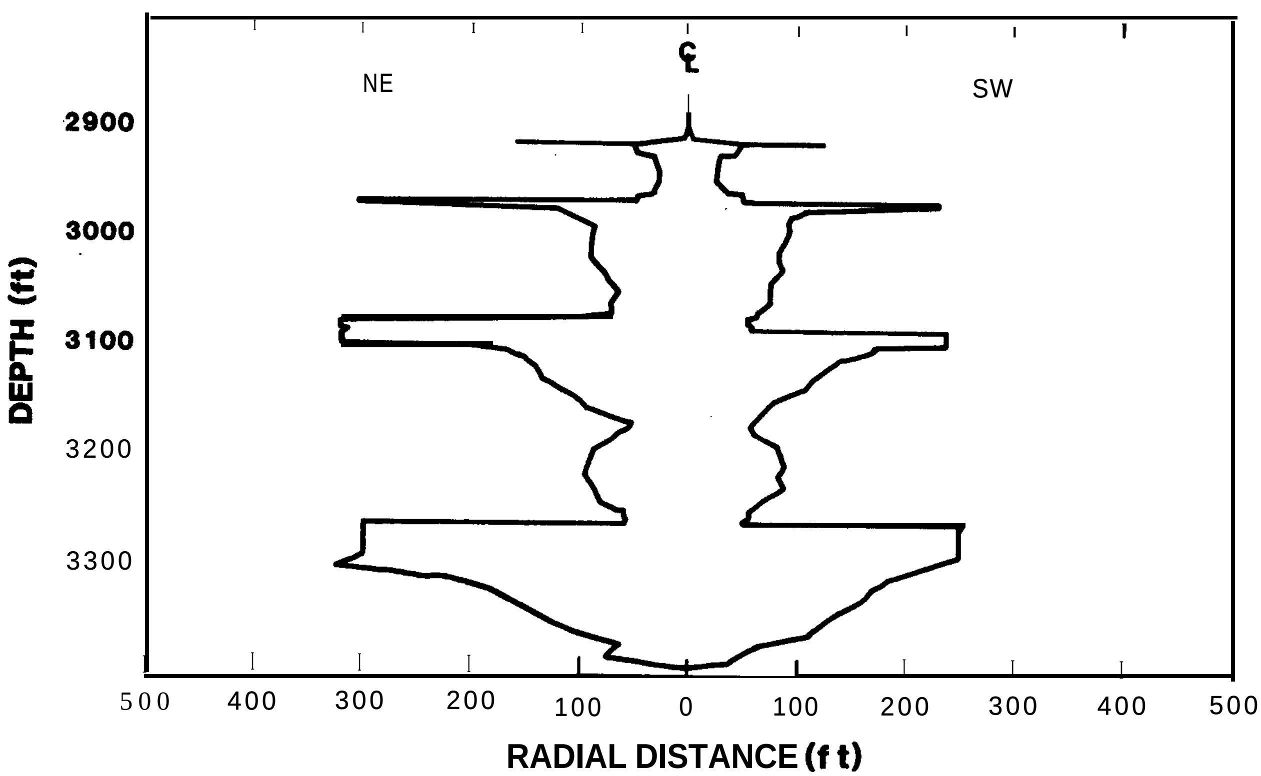

Figure 2. SM Cavern 6 Shape

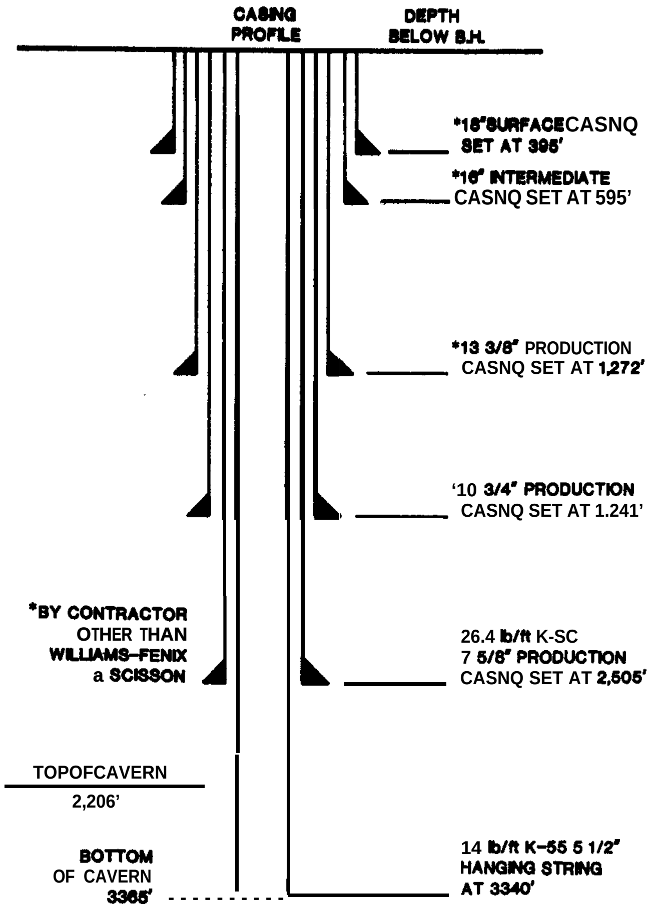

Figure 3. Well 6X Description

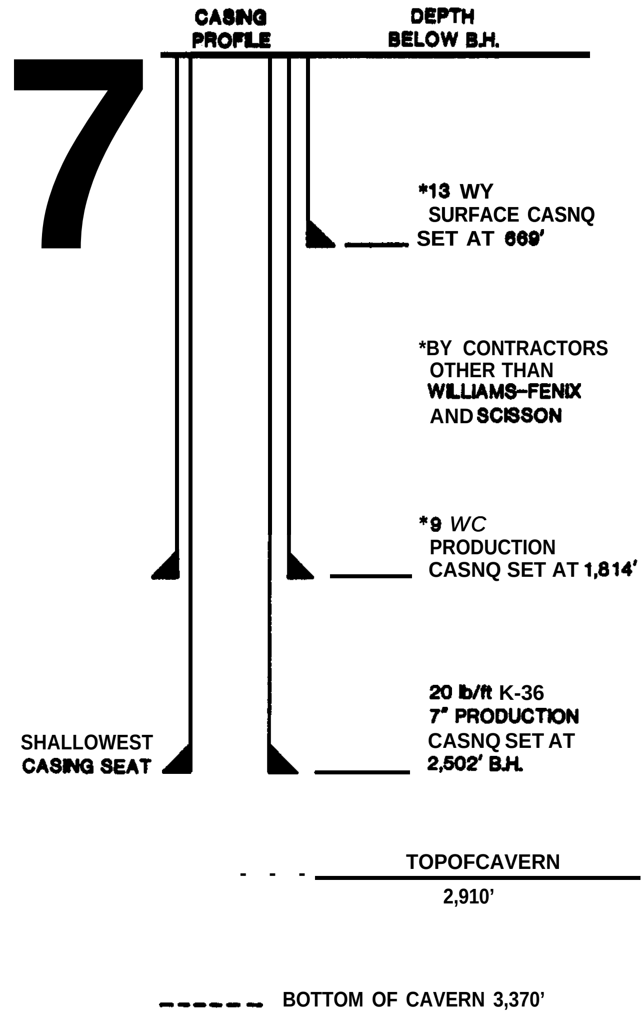

Figure 4. Well 6Y Description

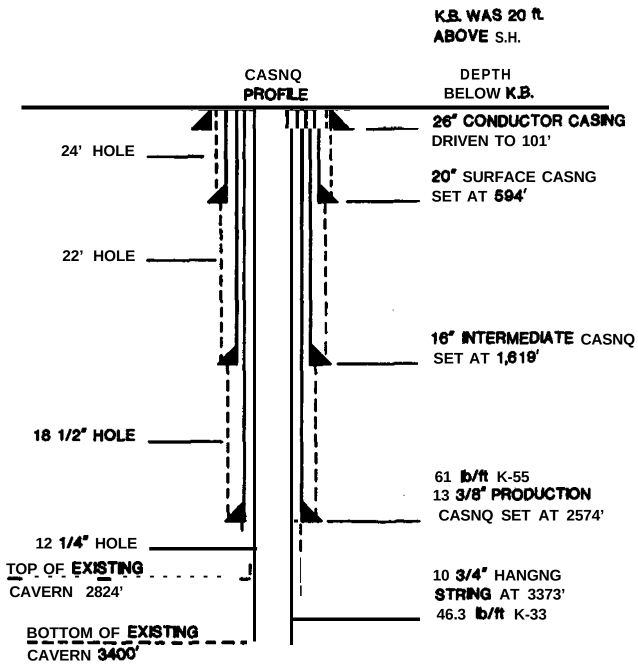

Figure 5. Well **6Z** Description

Table 1. SM 6 Interface and Temperature History

Date	Interface Depth Below Bradenhead (ft)	Temperature at 3100 ft (°F)	Comments
2/81	None	96.1 (6X)	Brine filled
Mid '82	—	—	Certification test and oil fill
Mid '83	—	—	Oil movements
11/83	3358 (6Z)	—	
2/84	3361 (6Z)	90.4	
4/84	3361 (6Z)	—	
4/84	3362 (6Y)	—	
8/84	3361 (6Z)	90.2	
12/84	3362 (6Z)	—	
2/85	3363 (6Z)	92.6	
5/85	3364 (6Z)	—	
5/85	3360 (6Y)	—	Possible reference error
8/85		93.5	

Linear regression of interface depths in **6Z** provides the equation
Depth = **0.2594** * (months since 1/83) + **3356.**

Sometime between the completion of testing in 1981 and the beginning of 1984 there apparently was a ledge fall that damaged the hanging string in well 6X. Sometime between April 1984 and May 1985 there apparently was another ledge fall, which raised the cavern bottom at well 6Y from 3404 to 3380 ft. This second apparent fall did not damage the hanging string in well 6Z and did not create a pressure disturbance detectable by the wellhead pressure instrumentation.

The testing of cavern 6 was started in March 1984 when the piping was installed[8] and the wellhead pressure instrumentation was assembled. Prior to this time the cavern had been operated by Petroleum Operating and Support Services, Inc. (POSSI) by taking pressure measurements with dial gages and by conducting brine removals to maintain the pressure within acceptable limits, but no measurements were made of the volume removed.

Test Methods and Results

The test procedure was to shut in the cavern, let the pressure increase to the desired level (200 to 500 psi), and then bleed brine through a 2-in turbine flowmeter to reduce the pressure to the desired level. Six bleed cycles were accomplished. The first bleed was to verify that the instrumentation was operating correctly and to obtain early estimates of the cavern's performance. This was followed by two high-pressure cycles (-500 psi), then a flowmeter calibration bleed on Test Day 285. The final series consisted of two cycles at lower pressure. The intent was to determine cavern performance at different pressures after rapid increases in salt stress during brine removal.

The pressure instrumentation included dial gages read by the on-site operations contractors (POSSI and BPSI), five pressure transducers coupled to an automated recording system, and the BPSI Gage 1 gun used as the on-site calibration/correction device for pressure corrections, if required. Total brine flow and flow rate were measured using a 2-in turbine flowmeter, with the total flow being recorded manually and on the automated recording system. A diagram of the piping system is shown in Figure 6. A block diagram of the data collection system is shown in Figure 7.

The pressure data are shown in Figures 8 through 12, temperature and pressure transducer supply voltages are shown in Figures 13 through 15, and brine removal data are shown in Figures 16 through 18.

The cavern elastic response, which includes the effects of salt and brine compressibility as well as the geometry, was calculated by taking the slope of the linear portions of the volume vs pressure curves in Figures 16 through 18 and averaging these eight linear-regression calculations. This cavern elastic response was derived from data taken at pressure change rates of -12 psi/hr. Pressure change rates significantly different than this will result in different elastic response values but we do not have sufficient data at this time to establish the sensitivity to the pressure change rate.

The cavern elastic response values shown in Figures 16 through 18 appear to increase with time at a slope of 2 to 3 bbl/psi per year. The resolution of the data is not sufficient to determine if this is real data or if this is possibly an artifact of some other variable in the system. The trend is correct because an increase in temperature will result in increased compressibility values for both oil (-0.017×10^{-6} bbl/bbl/psi/°F) and for salt (-0.006×10^{-6} bbl/bbl/psi/°F). The pretest calibration of the flowmeter showed less than a 2% error (Appendix A) but no posttest calibration was conducted because the flowmeter was left in the field for potential future use.

The cavern salt elastic response was calculated by subtracting the total oil compressibility (Figure 19) and the total brine compressibility (Figure 20) from the total cavern elastic response, then dividing by the total cavern volume.

$$0.80 \times 10^{-6} \text{ bbl/(bbl psi)} =$$
$$(40 \text{ bbl/psi} - 5 \times 10^{-6} \text{ l/psi} \times 6.79 \times 10^{6} \text{ bbl} -$$
$$2.1 \times 10^{-6} \text{ l/psi} \times 0.21 \times 10^{6} \text{ bbl})/7.00 \times 10^{6} \text{ bbl}.$$

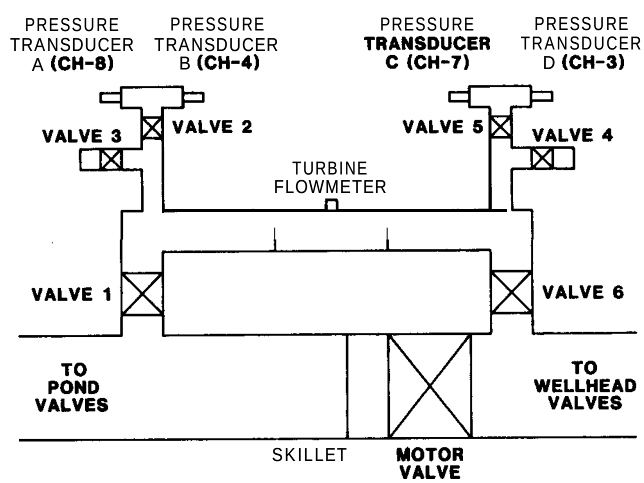

Figure 6. Piping Diagram of Creep Test on SM 6

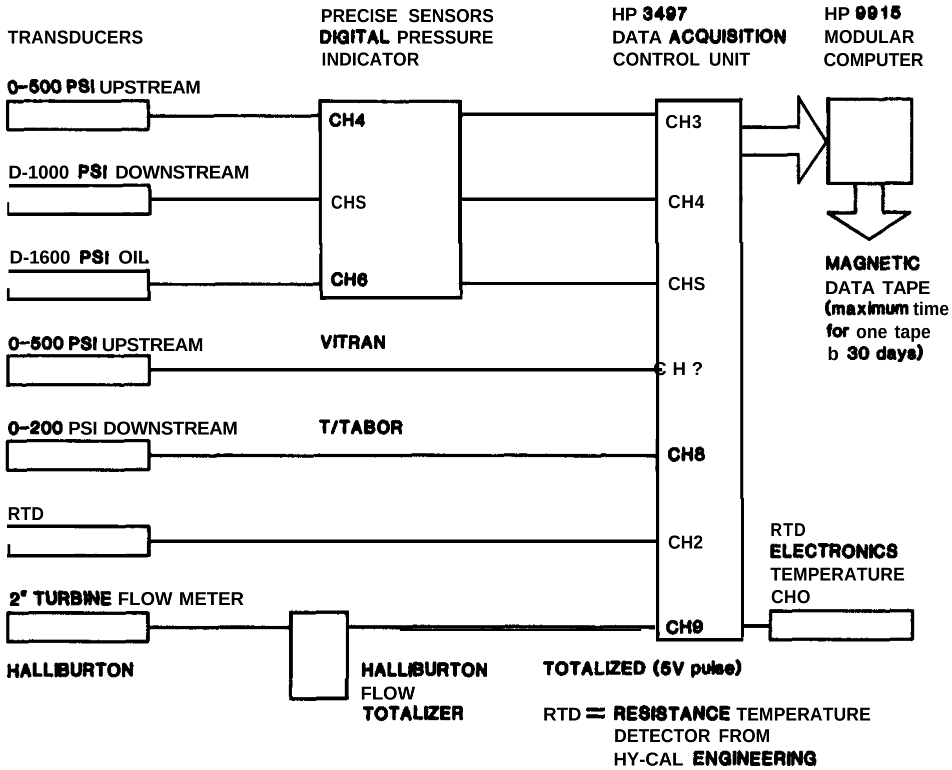

Figure 7. Block Diagram of Creep Test Instrumentation

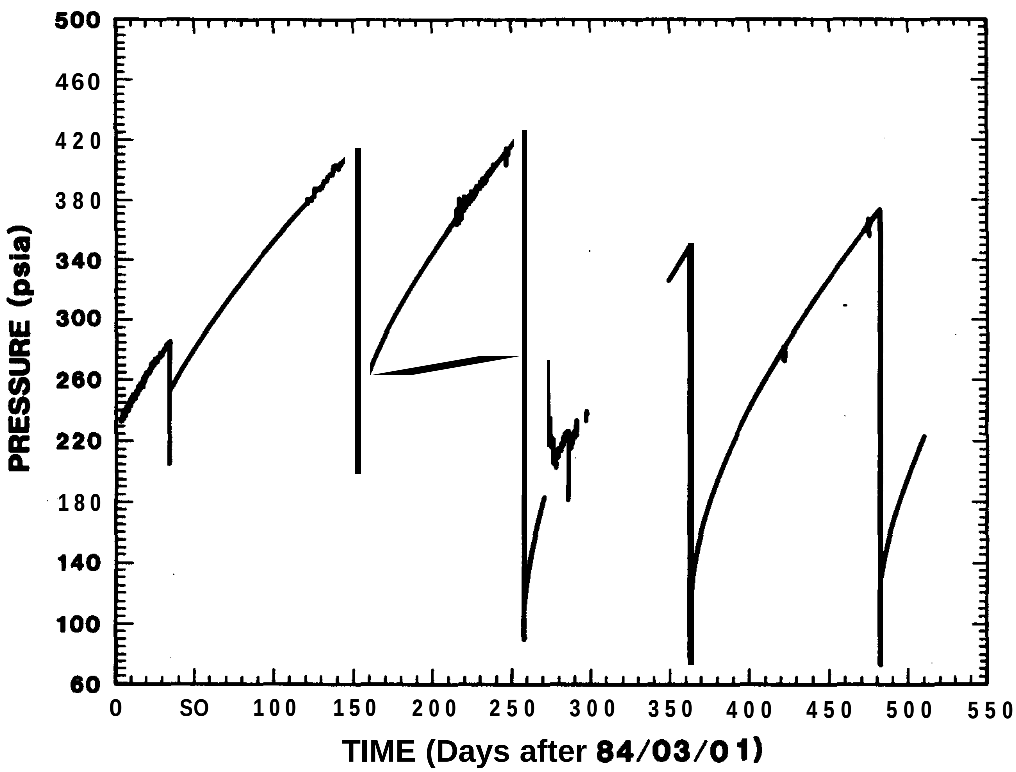

Figure 8. Brine Pressure vs Time Ch3

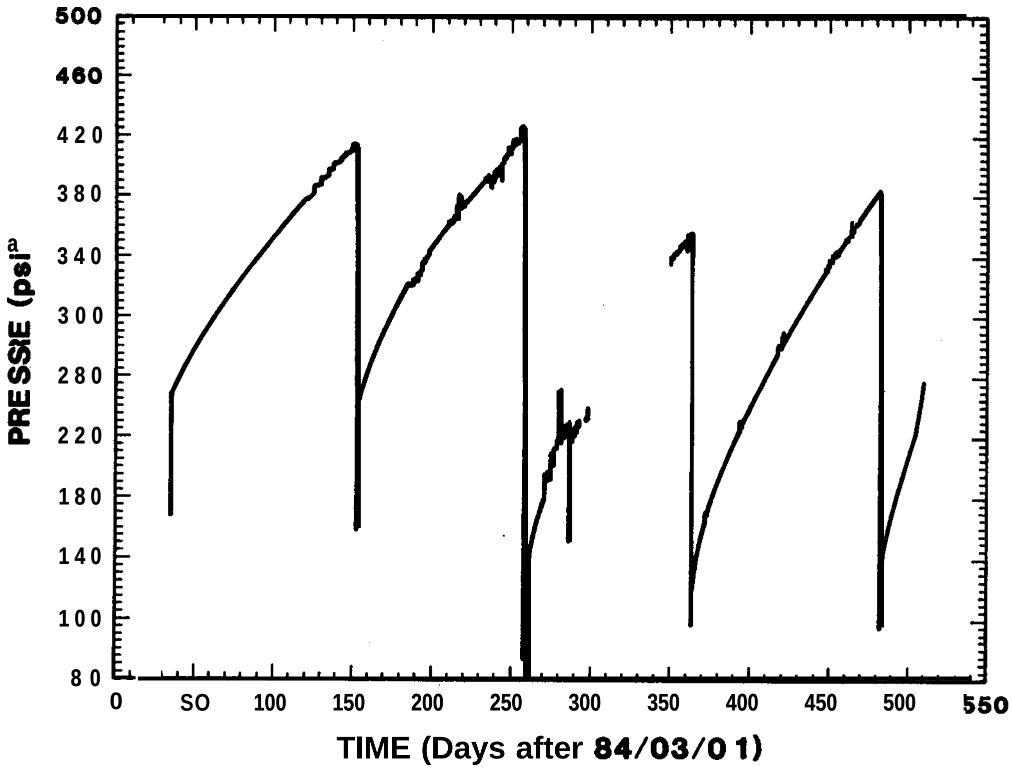

Figure 9. Brine Pressure vs Time Ch4

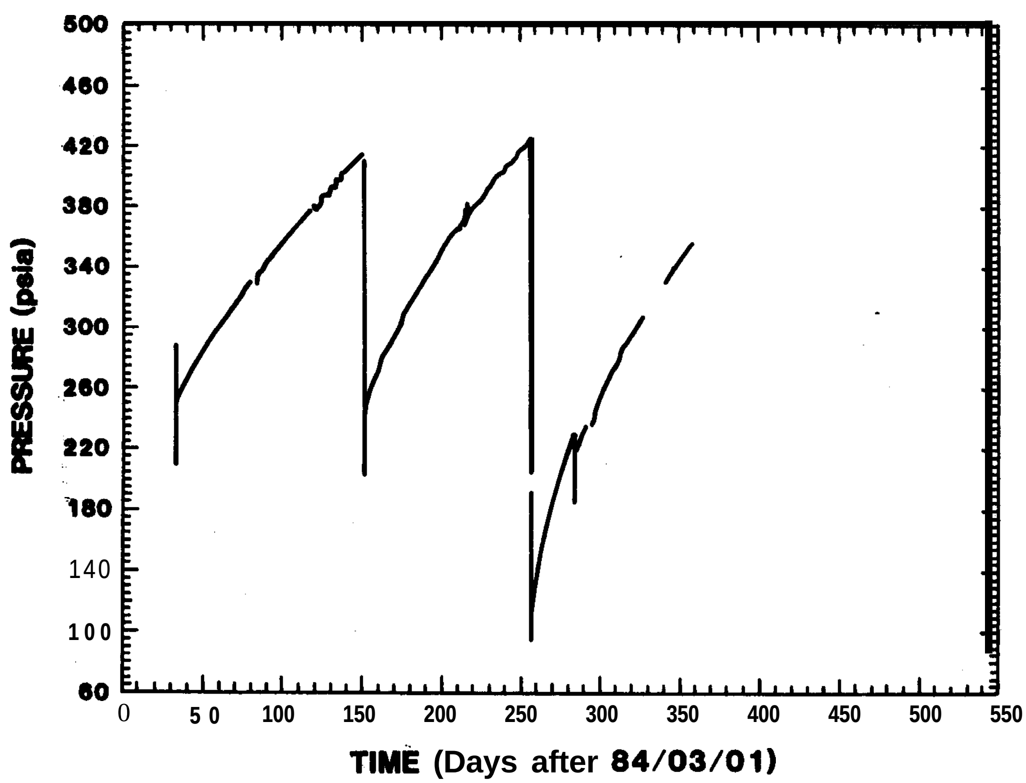

Figure 10. Brine Pressure vs Time Ch7

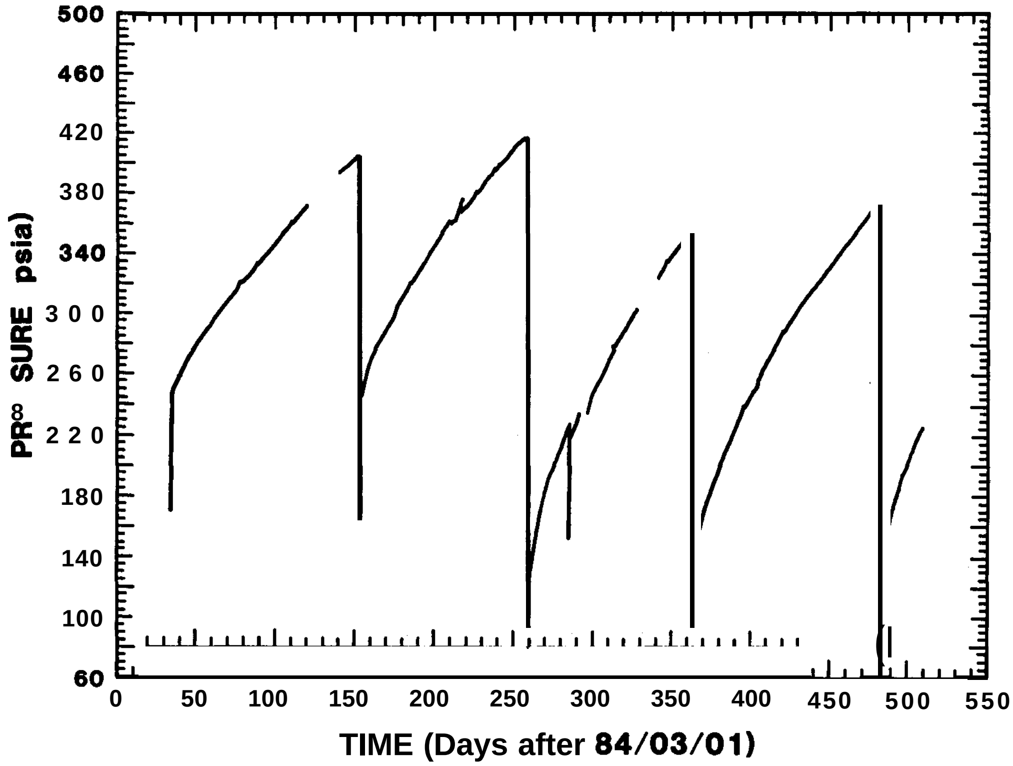

Figure 11. Brine Pressure vs Time Ch8

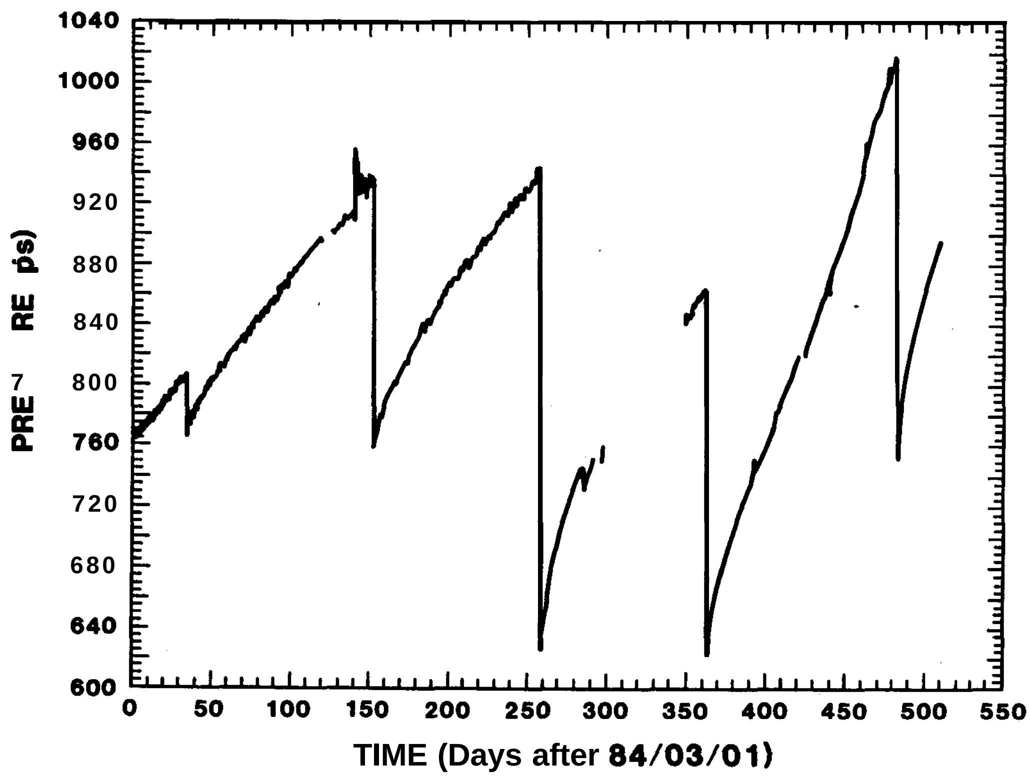

Figure 12. Oil Pressure vs Time Ch5

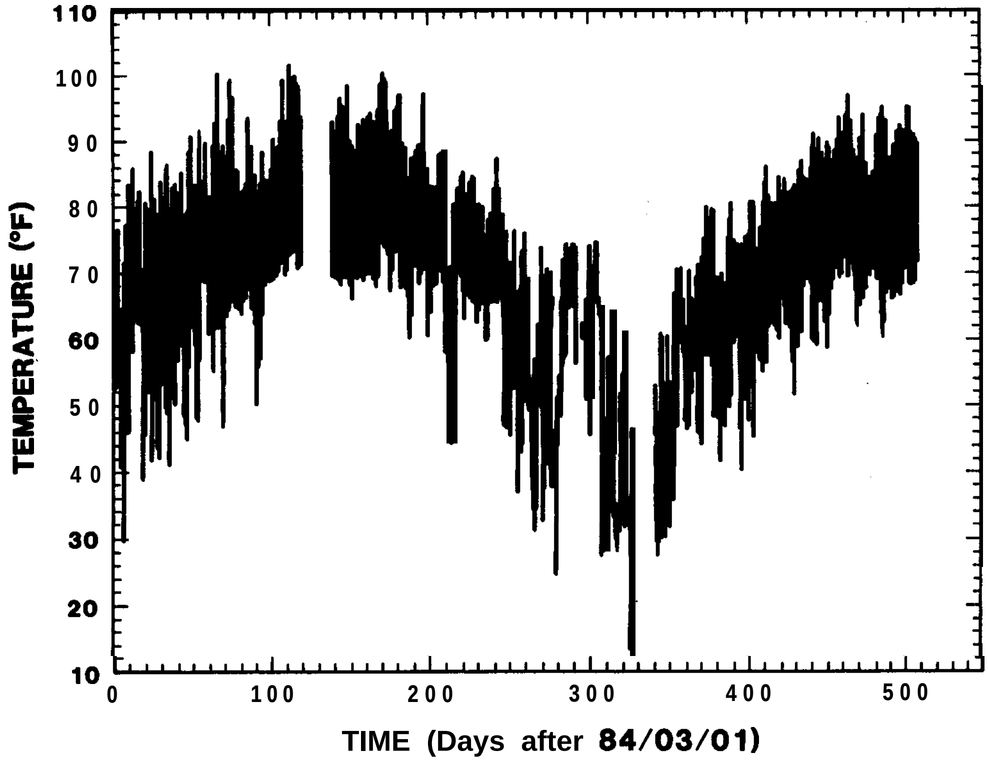

Figure 13. Transducer Temperature vs Time Ch2

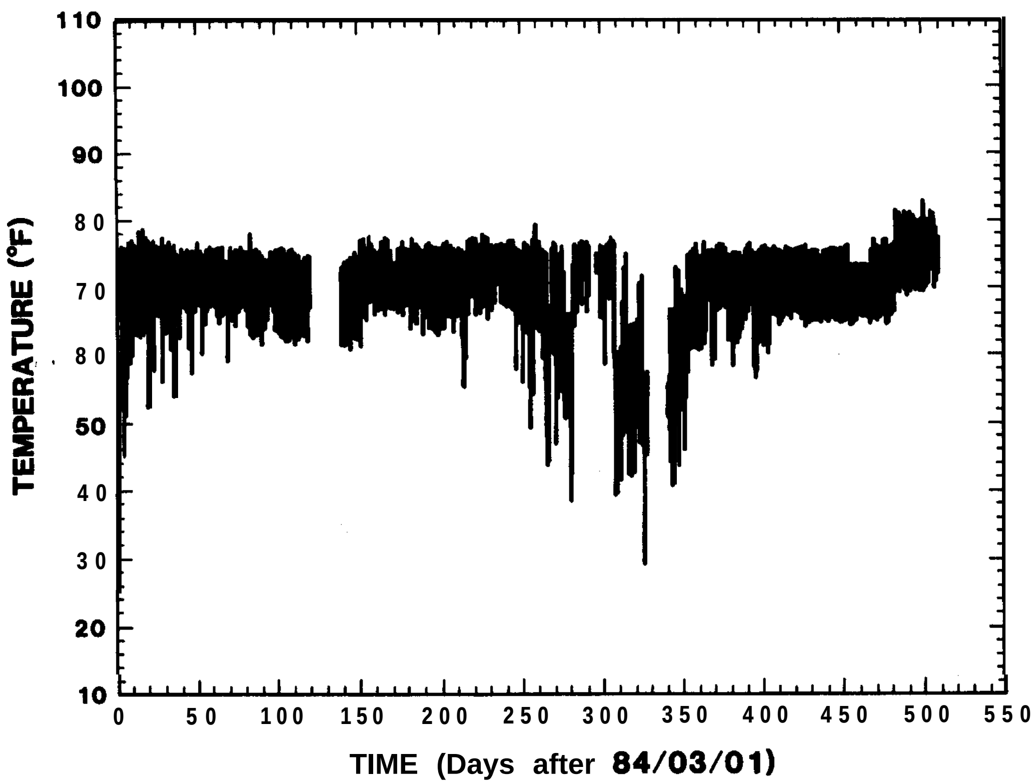

Figure 14. Electronics Temperature vs Time Ch0

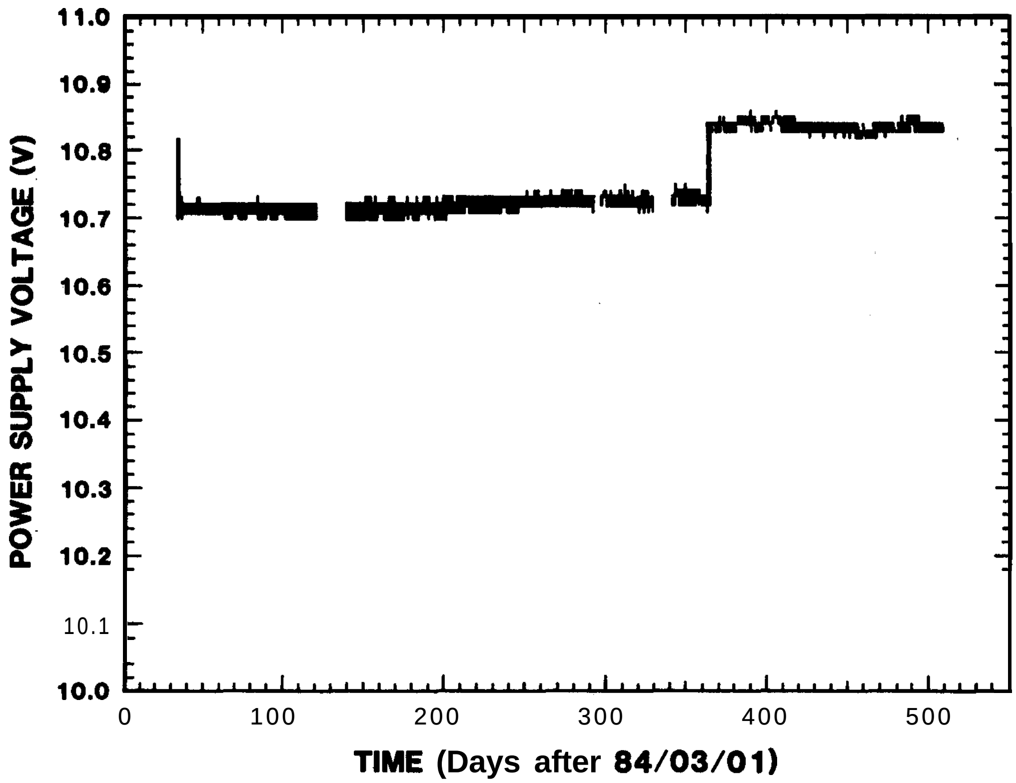

Figure 15. Ch7 and Ch8 Power Supply Voltage vs Time Ch6

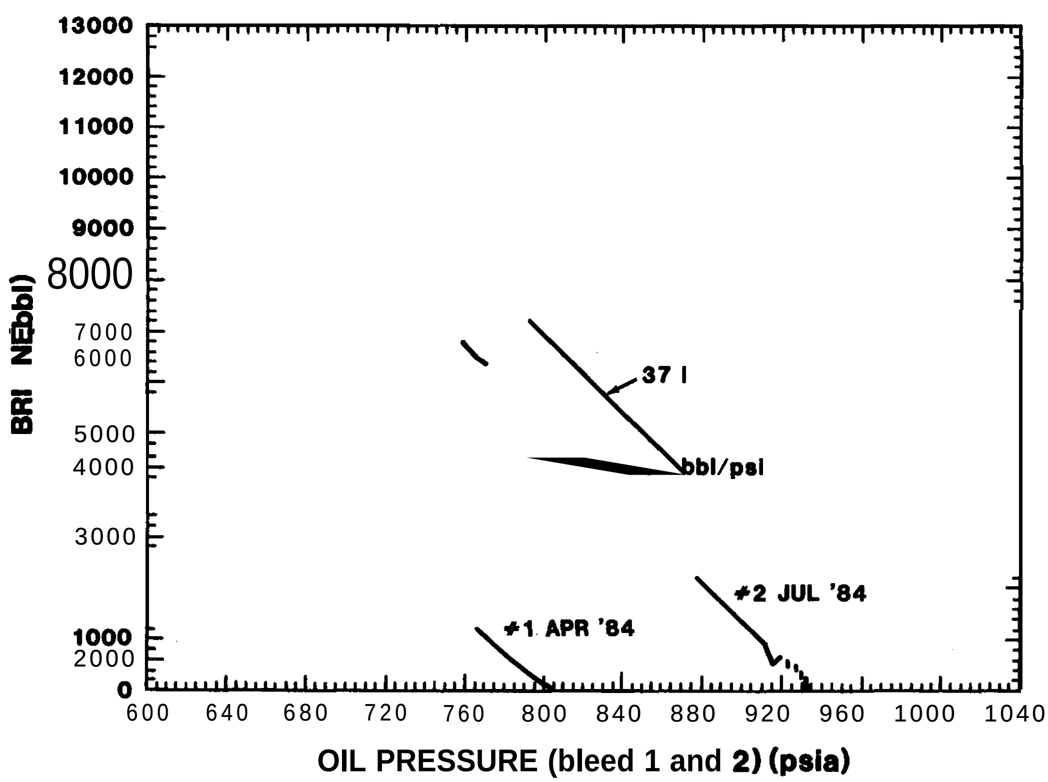

Figure 16. Brine Removed vs Pressure (bleed 1 and 2)

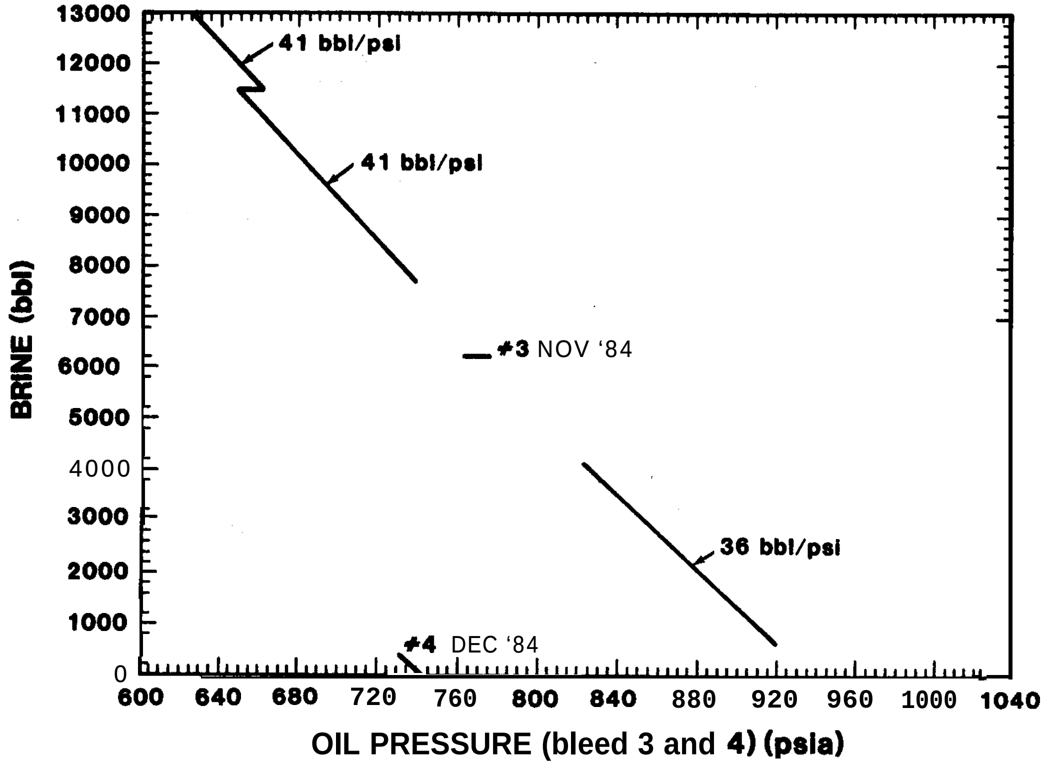

Figure 17. Brine Removed vs Presgure (bleed 3 and 4)

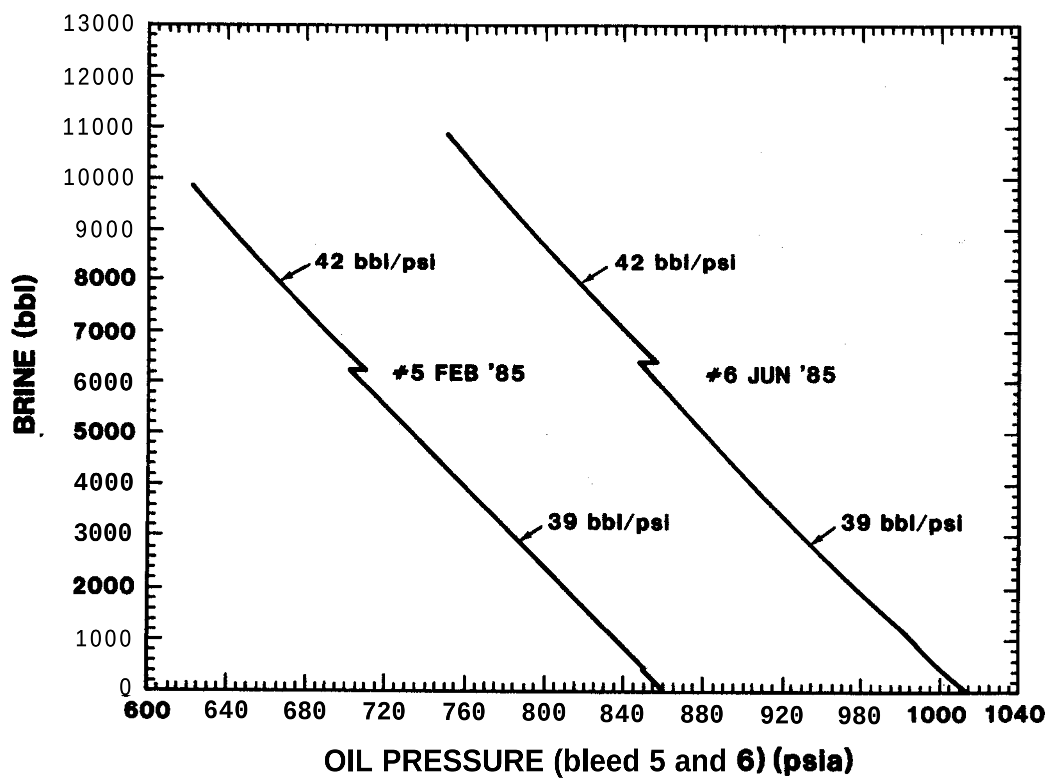

Figure 18. Brine Removed vs Pressure (bleed 5 and 6)

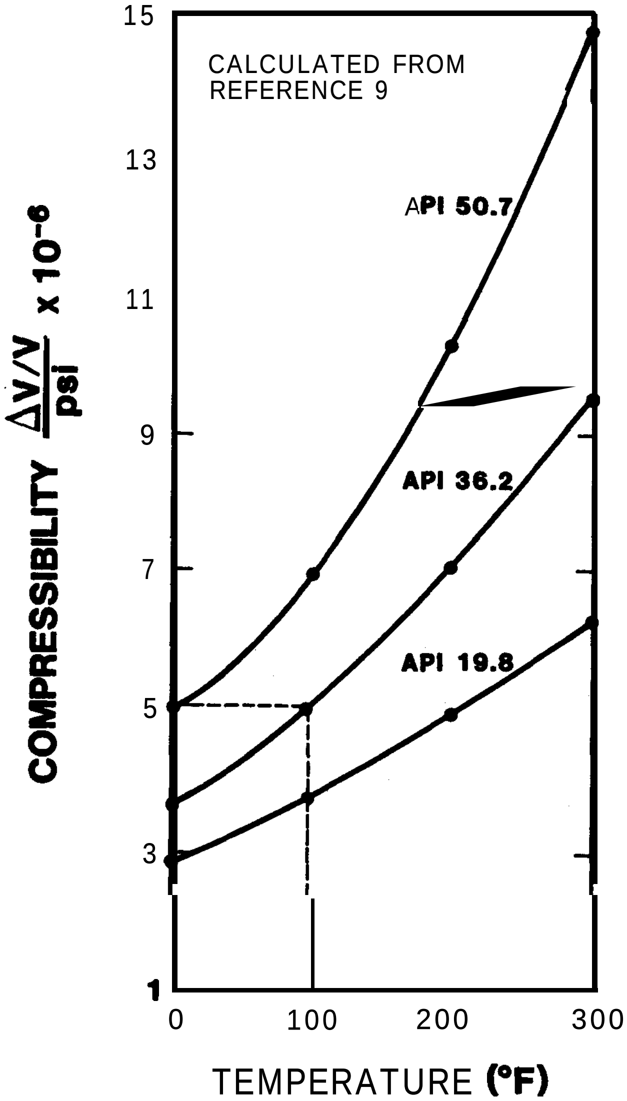

Figure Ig. Oil Compressibility vs Temperature

FROM:
Potter, Robert W., II and Brown, David L., "The Volumetric Properties of Aqueous Sodium Chloride Solutions From 0° to 500° at Pressure up to 2000 Bars Based on a Regression of Available Data in the Literature", Geological Survey Bulletin 1421-C, U.S. Government Printing Office, 1977.

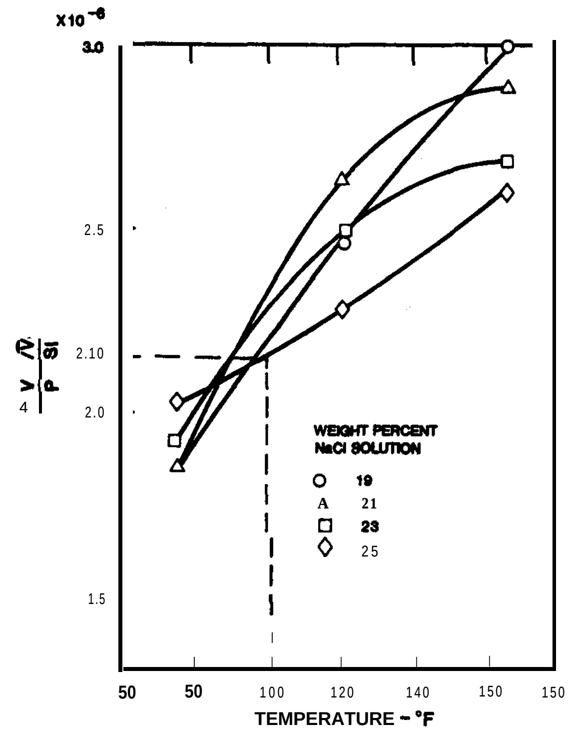

Figure 20. Brine Compressibility vs Temperature

The calculated bulk modulus of salt from the WH materials test was -4.6 $\times 10^6$ psi, which converts to a compressibility of -0.22 $\times 10^{-6}$ psi. If this value is compared to the calculated 0.80 $\times 10^{-6}$ value above, it appears that the volume of salt that is effective in the elastic response is significantly more than the cavern volume.

The cavern closure was calculated by taking the total brine that was removed from the cavern from the start of the test until the pressure on June 25, 1985, was equal to the starting pressure, dividing by the total time, and correcting for pressure and temperature:

73 bbl/day = 35150 bbl/482 days and 73/40 = 1.8 psi/day.

The cavern temperature logs taken from February 1984 through August 1985 show a 2°F temperature rise per year. Additional logs taken in the future will allow better determination of the exact temperature change rate, but the 2°F/yr rate will be used for the calculation of oil thermal expansion. The oil thermal expansion coefficient was calculated based on 36.2' API oil at 2500 psi as 2.9 $\times 10^{-4}$ bbl/bbl°F using the specific gravity curves in Reference 9. The oil volume change was, therefore, calculated as

11 bbl/day = (2.9 X 10^{-4}/deg X 6.79 X 10^6 bbl X 2 X deg)/365 days and 11/40 = 0.3 psi/day.

The rates of pressure increase were calculated using a linear regression for 10 days at the indicated pressure region for each channel and then averaging all the applicable channels. The result of this procedure is that each of the three quoted pressure rise rates are based on approximately 1200 data points. A review of pressure vs time curves in Figures 8 through 12 indicates that the shape and slope of the curves immediately after a pressure reduction are a function of both the pressure and the magnitude of the pressure reduction. After a period of time, the curve slopes appear to be a function of the pressure only, and are independent of the magnitude of the pressure reduction. Many contributing factors are undoubtedly involved in this behavior, but there are surely contributions from salt creep and salt stress redistribution. Any change in internal or external pressure will generate a change in the salt creep rate and in the salt stress distribution, and both will then change with time toward a new steady-state condition.

The cavern pressure behavior after each of the five significant pressure reductions was analyzed in 24-hour linear regression steps for 15 days. The calculated pressure increase rates were plotted against the time in days after the pressure reduction. The boundaries of these data were then curve-fit with a power equation of the form

psi/day (y) = constant (a) days $(x)^{\text{constant (b)}}$.

The curve fit for a small pressure reduction at relatively high pressure similar to the reduction at Day 33 was

$y = 3.3\ (x^{-0.466})$ which is approximately $3.3/x^{0.5}$

The curve fit for a large pressure reduction at relatively low pressure similar to the reduction at Day 260 was

$y = 13.6\ (x^{-0.533})$ which is approximately $13.6/x^{0.5}$

The cavern pressure behavior beyond the initial 15-day period was analyzed in 10-day linear regression steps until the next pressure reduction. The calculated pressure increase rates were plotted as a function of the average brine pressure during the calculation interval and then curve-fit with a linear equation of the form

psi(z) = constant(c) + constant(d) pressure increase (yl in psi/day).

The resulting linear fit was

z = 527 − 130 (yl in psi/day)
[when z = 0, yl = 4].

Then, setting y = yl and solving for the time (x) when the slopes are equal indicates that the effects of the pressure reduction will be significant for up to 60 days after a large pressure change at relatively high (z = 300 psi) brine pressure and as short as 1 day after a small pressure change at relatively low (z = 100 psi) brine pressure. A linear extrapolation of the temperature-corrected data (using 2°F/yr = 0.3 psi/day) to zero wellhead brine pressure (z = 0) gives a pressure increase rate of 3.7 psi/day. This curve fit was done using 11 data points in the Hewlett-Packard LIN program, which produced a coefficient of determination equal to 0.83.

Analyses of these data provide the following typical parameters:

Total cavern elasticity = 40 bbl/psi

Salt cavern elasticity = 0.80 X 10^{-6} bbl/(bbl psi)

Cavern closure including thermal expansion = 73 bbl/day, which translates to -1.8 psi/day

Oil thermal expansion based on +2°F/yr = 11 bbl/day, which translates to -0.3 psi/day.

Cavern pressure increase rates are approximately

- 0 psi/day with oil pressure near 1050 psig (linear extrapolation)
- 1 psi/day with oil pressure near 944 psig
- 2 psi/day with oil pressure near 785 psig
- 4 psi/day with oil pressure near 520 psig (linear extrapolation)
- 5 psi/day with oil pressure near 630 psig within 10 days after a large pressure reduction.

The repeatability of the pressure data is affected by many things in the field environment. For example, the interruption of the pressure data in Figures 8, 9, and 12 from Day 300 to Day 350 was due to a failure of the Precise Sensor Inc. digital pressure indicator package, and when this package was replaced, the oil transducer on channel 5 had excessive drift or calibration errors. This was not apparent until the data were processed at approximately Day 450 and the Ch5 slope was compared to the other pressure curve slopes. An example disturbance can be seen at Day 405 in Figures 8 through 12 when the pressure increased -3 psi in 6 hours because of a pressure reduction in cavern 7 as a result of an oil drawdown. The Precise Sensor Inc. system performed reasonably well in the field environment with no preventive maintenance (system No. 1 lasted 314 days without a failure). The second system experienced a problem on Ch5 from the beginning, and then Ch4 developed excessive drift starting at about Day 500.

Other causes such as electrical storm disturbances and power outages can create anomalous readings such as those near Days 215 and 420. Other artifacts in the data such as the pressure spike in Figure 8 at Day 270 have not been explained, but the other channels of data indicate that this was indeed a disturbance in the instrument system and not in the cavern. When these short-time disturbances are ignored in the data set and all the pressure channels are compared, the potential error in pressure readings is illustrated in Figure 21, which includes all the pressure data. It also includes Ch5 up to Day 300 (Ch5 minus 520 psi is plotted). The error illustrated in Figure 21 is a maximum of 13 psi at 370 psia on Day 480, which is less than ± 2 % total on three data channels.

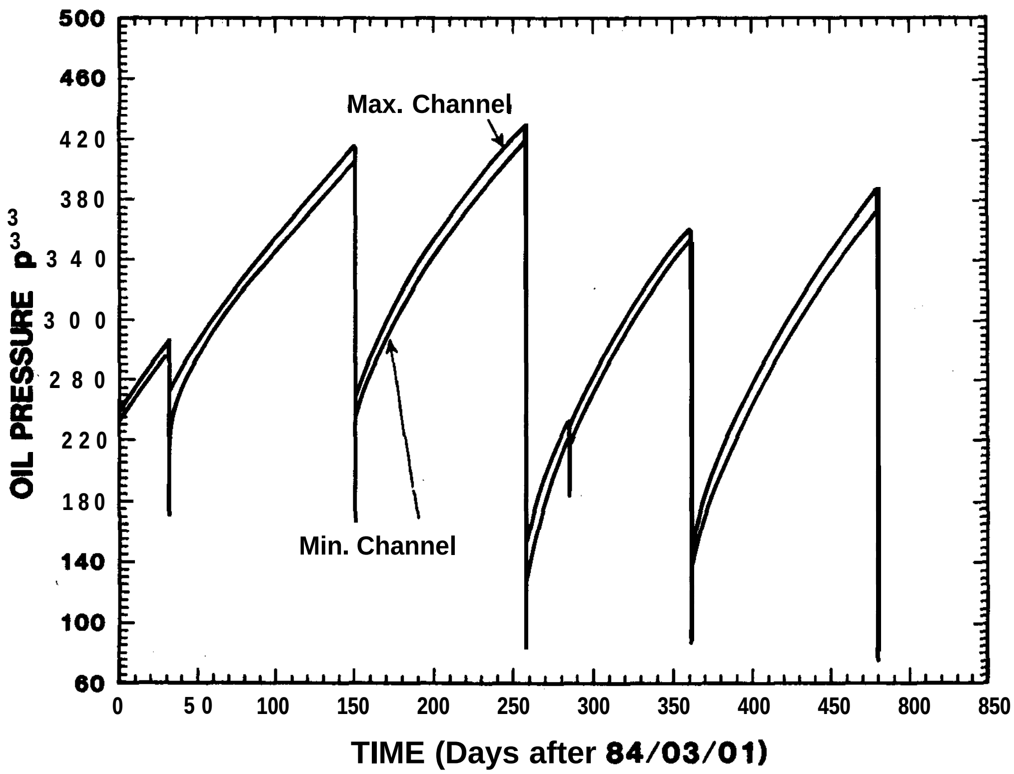

Figure 21. Repeatability of Pressure Data on Five Channels

The 2% error indicated includes the effects of transducer errors, temperature effects, conversion errors in the electronics system, and rounding errors. Both the temperature of the transducer and the temperature of the electronics package have an effect on the pressure readings, but the combined effects of both temperatures is $<$ 0.5% of the reading. (The lab test data in Appendix B show a variation of $\sim 1/4\%$ due to transducer temperatures.) The errors associated with conversion and rounding are still smaller than the temperature error. Therefore, the errors are assumed to be dominated by transducer errors even though the manufacturer quotes the transducer to be better than $\pm 0.25\%$ of full scale (equivalent to less than $\pm$ 0.5 % of test pressure).

Some comparisons of cavern parameters from the creep-closure tests and the certification tests are shown in Tables 2 and 3. To do a rigid evaluation of the "other elastic" response values, it would be necessary to obtain actual compressibility data for the cavern oil, but some things can be noted relative to Table 3. Cavern 2-4-5 at SM is a gassy, three-cavern gallery and a high elastic response would be expected. Cavern 6 at WH has a flat roof nearly 1200 ft in dia, which could be flexing and generating a large elastic response. Cavern 2 at BM has a flat roof -600 ft in dia and is probably gassy, which would tend to generate a large elastic response.

The test on SM 6 was terminated in July 1985 to allow the instrumentation to be calibrated and repaired prior to its use on other cavern tests as directed by DOE Technical Directive No. 92. The instrumentation calibrations before and after the test are shown in Appendix A.

Table 2. Comparisons of Caverns Using Creep-Closure Data

	SM6	WH 11
Oil fill dates	1981-1982	1978-1981
Cavern volume (bbl)	7.0×10^6	8.5×10^6
Oil volume (bbl)	6.8×10^6	8.2×10^6
Total depth (ft)	3390	3760
Roof depth (ft)	2910	2940
Total cavern elasticity (bbl/psi)	40	49
Fluid elasticity (bbl/psi)	34	42
Other elasticity (bbl/psi)	6	7
Total cavern closure including thermal effects (bbl/day)	73	60
Volume change due to temperature rise of 3°F/day (bbl/day)	16	20
Creep closure (bbl/day)	57	40
Oil gravity (deg API)	32.7	33.1

Note: The two caverns were not operated at the same pressures; therefore, the closures are not directly comparable.

Table 3. Comparisons of Caverns Using Data from Certification Tests

Cavern Oil	Total Volume	Oil Volume (MMBBL)	Total Depth (MMBBL)	Roof Depth (ft)	Measure-ments (ft)	Fluid Elasticity	Other Elasticity	API Degree Elasticity
SM6	7.0	0	3400	2910	21.5	14.7	6.8	NA
SM7	7.0	0	3185	2770	20.5	14.7	5.8	NA
SM 245	13.3	0	3356	2447	70	28	42	NA
WH6	8.5	0	3389	3225	57	18	39	NA
BC 18	11.1	10.3	4225	2100	53	53	0	36.2
BC 20	8.4	0	4291	3825	21.6	17.6	4.0	NA
BC 20	8.4	7.1	4291	3825	42	38	4.0	36.3
BC 102	5.5	0	3460	2640	13.8	11.6	2.2	NA
BM 1	8.0	7.8	2778	2320	48	39.4	8.6	36.6
BM2	6.4	6.1	1680	1450	113	31.1	82	35.9
BM5	37.5	33.9	3322	2110	201	177	24	36.2
BM 104	11.7	11.0	4180	2120	64.3	56.5	7.8	

Notes:
1. Volumes taken from July 1985 BP81 daily report.
2. Depths taken from Reference 10.
3. Fluid elasticity values used were 5.0 X 10^{-6} l/psi for oil and 2.1 $\times 10^{-6}$ l/psi for brine.
4. Elasticities are in bbl/psi.

Mathematical Models

Two models will be described, and their results will be compared to the cavern test data.

Thermal Model

The thermal model is described in detail and is compared to test data from WH cavern 11 and BM cavern 4 in Reference 11. The results of sensitivity studies for the thermal model are described in Reference 12. SM cavern 6 was not modeled specifically, but some general comparisons can be made with the WH 11 cavern. The temperature increase in WH 11 about 3 years after oil fill was ~3.4°F/yr. This cavern is deeper than SM 6, and the increased depth would result in increased heat flow into the cavern. WH 11 is larger than SM 6, which would result in a slower temperature rise for a given heat flow into the cavern. Therefore, it is reasonable to expect that the temperature rise in SM 6 would be similar to the WH 11 temperature rise. The four temperature logs taken since oil fill indicate that the SM 6 temperature rise is ~2°F/yr. Additional logs to be taken in the future will allow for a better definition of the temperature rise.

The sensitivity studies performed for the thermal model and reported in Reference 12 indicate that the following models are essential for correct temperature prediction: a counterflow heat exchanger model, a mixing model, and a model for interfacial heat transfer between the brine and the oil. The thermal calculations were most sensitive to variations in salt conductivity and to initial fluid temperatures.

Structural Model

The finite element method has been used for several years to model the structural stability and creep closure of SPR caverns. Finite element structural creep analyses have been performed on most caverns in the SPR. Most of these analyses are discussed in References 12 through 15. The finite element calculated creep closures and associated pressure rise vs time are below field data by a factor of 2 for some caverns and are closer for others.

The finite element creep formulation uses a secondary creep model that has the one-dimensional form of

$$\dot{e} = A\,(S)^n$$

where $\dot{e}$ is the secondary creep strain rate, A is a laboratory-determined, temperature-dependent constant, S is effective stress, and n is the stress exponent

(Appendix B). A three-dimensional tensorial form of the creep model enables calculation of displacements and stresses as functions of time over the life of the cavern. As discussed in Appendix B, the cavern geometry is approximated with a two-dimensional axisymmetric finite element mesh. Boundary conditions and body forces are applied to simulate in situ stresses around the cavity. Boundary conditions on the cavern itself are varied with time to simulate leaching the cavern from a borehole to its present shape.

The finite element model of this cavern is discussed in more detail in Appendix B. The best approximation of the cavern geometry includes ledges and gives a pressure change rate of 4.2 psi/day for the cavern when it is at brinehead pressure. An extrapolation of the field data from the working pressure (300 to 600 psi wellhead pressure) down to brinehead pressure (0 psi at the wellhead) gives a pressure change of 3.7 psi/day. This shows a 14% overprediction by the finite element model, which seems within reasonable bounds of error.

The cavern salt elastic response was calculated using the finite element model. Cavern-surface pressure was increased from brinehead pressure to 300 psi above brinehead over 150 days, and then was instantly reduced back to brinehead pressure. The cavern salt elastic response was calculated by dividing the volume change experienced during the pressure drop by the corresponding pressure drop, and then dividing by the cavern volume. Cavern salt elastic response calculated in this manner was 0.57 X 10^{-6} bbl/(bbl psi) compared to 0.80 x 10^{-6} bbl/(bbl psi) obtained from field pressure experiments.

Current and Future Test Plans

Tests at West Hackberry cavern 11 and well 112 were completed in October 1983 and reported in Reference 1. Testing of Bryan Mound cavern 2 was started in August 1984, but the creep instrumentation was removed in April 1985 when the Long-Term Monitor (LTM) instrumentation system became available for that cavern. Testing of Bryan Mound cavern 5 began in August 1984, was interrupted for the cavern certification test in June 1985, and will continue through 1986 to obtain data through multiple cycles of pressure buildup and bleeddown. Testing of the first 10 Big Hill wells began in January 1984, the second 10 wells began in June 1985, and the last 8 wells were started in August 1985. These tests will continue until cavern leaching starts or when it is determined that the risk of hanging-string capture by salt creep is acceptably small and the tests can be terminated. Testing of Bayou Choctaw caverns 18 and 20 is expected to start in early 1986 and continue for about 1.5 years.

These creep data will be combined with the information from the temperature logs, cavern oil/brine interface logs, and certification test data to make inputs to the temperature models and the structural models. These creep-test data, the early LTM data, and the mathematical models will form the basis for cavern behavior predictions that influence the operational requirements of the SPR program.

Conclusions and Recommendations

The conclusions reached from the test operation and the data are as follows.

- This test method provides usable data for mathematical model comparisons and for baseline data to be used in the LTM program.
- The cavern mathematical models are in reasonable agreement with the field data, but continued development is required to include additional variables and to verify the effects of cavern shape, cavern depth, salt properties, and salt temperature.
- Finite element analyses of several different models of SM6 indicate a strong correlation between creep closure rate and total cavern volume.
- Accurate temperature logs and oil/brine interface logs should continue to be taken and analyzed along with the pressure data.
- Sulphur Mines cavern 6 appears to be behaving in a consistent and stable manner, similar to its behavior during the certification testing in 1981. The suspected ledge falls have not caused detectable changes in cavern behavior.

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[15]D. S. Preece and W. R. Wawersick, “Leached Salt Cavern Design Using Fracture Criterion for Rock Salt,” *Proceedings of 25th U.S. Symposium on Rock Mechanics,* Northwestern University, June 1984.

[16]D. S. Preece and J. T. Foley, *Long-Term Performance Predictions for SPR Salt Caverns,* SAND83-2343 (Albuquerque, NM: Sandia National Laboratories, November 1984).

APPENDIX A

Instrument Calibration

The accuracy of the instrumentation was determined prior to the test for use in data interpretation and analysis. Instrument certification was done by the Sandia Laboratory Measurement Standards Department.

Exhibits A and B show the results of the Precise Sensor Inc. digital pressure indicator system calibrated in November 1983. This system was certified accurate within ±0.25% of the full-scale value. Exhibit C shows the results of the pressure hysteresis test. Exhibit D shows the results of the pressure stability test and the effects of transducer temperature. These tests were run to simulate the expected field environment of the SM 6 test. This system was used from March 1984 until January 1985, when it failed to operate properly and was returned to the manufacturer for repair.

Exhibits E and F show the results of the Precise Sensor Inc. digital pressure indicator system calibrated in January 1985. This system was certified accurate within ±0.25% of the full-scale value. It was used from February 1985 until the end of the test in July 1985.

Exhibit G shows the results of the March 1984 calibration tests of Vitran (used on channel 7) and Teledyne Taber (used on channel 8) transducers which were put on the test for transducer evaluation and to provide a backup data source. The Vitran transducer was certified accurate within ±0.25% of the full-scale value and the Teledyne transducer was certified to be within ±0.30% of the full-scale value. The Vitran transducer was used from April 1984 until February 1985, when it failed to operate properly. The Teledyne transducer was used from April 1984 until the end of the test in July 1985.

Exhibit H shows the results of the November 1983 calibration of the Halliburton turbine flowmeter and readout unit. The flow rate indicated was within ± 2.5% of the actual flow rate over the temperature range of 65°F to 150°F with pure water. The measured pressure drop of the field flow data matches the pressure drop calculated with pipe flow theory, using a pipe roughness of 0.00018 ft, plus the turbine pressure drop, as published by Halliburton Services, and shown in Figure Al.

Exhibits I and J show the results of the posttest calibration of the transducers that were functional at the end of the test. Comparison of these data with the data in Exhibit E through G indicates that the transducer accuracies were degraded by as much as 2.4 % of full scale at room temperature.

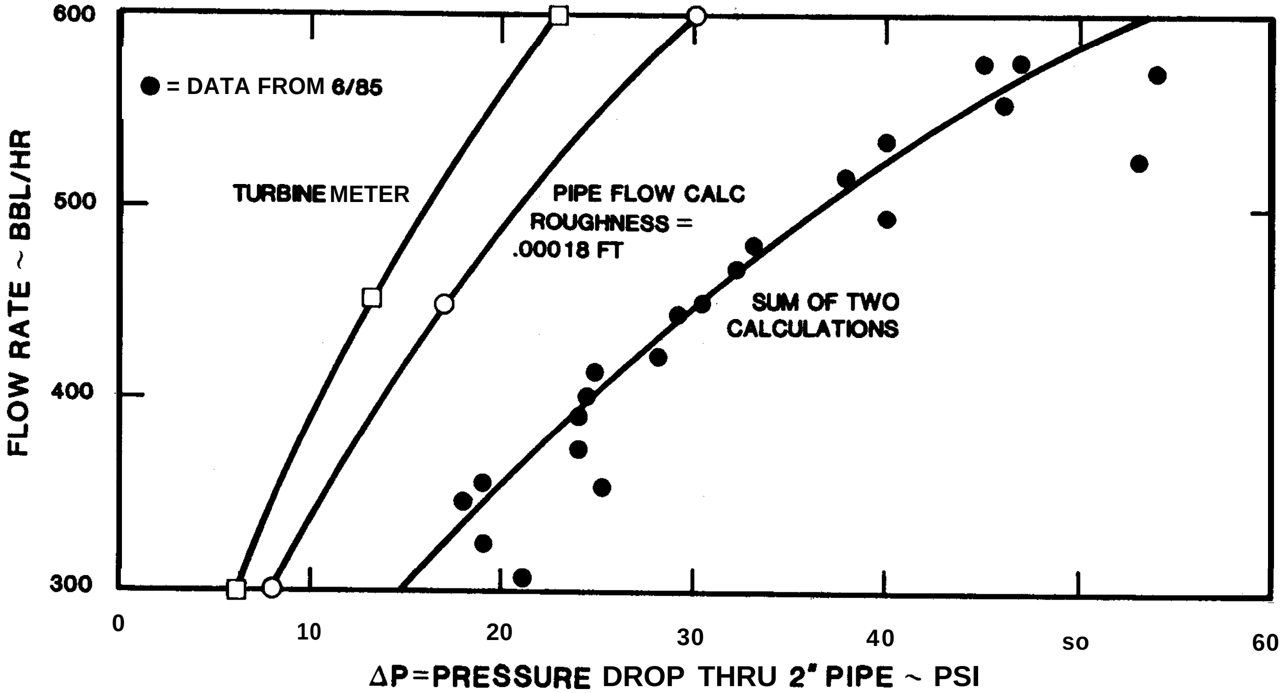

Figure AI. Flow Rate vs Pressure Drop Through 2-in Piping

Exhibit A

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7546 11/14/1983

MANUFACTURER PRECISE SENSOR
MODEL 6540-500-A-B
SERIAL 21293/CH 3
TRRNSDUCER TYPE TRRNSDUCER AND AMPLIFER SYSTEM
CERTIFIED BY WH
EXPIRATION DATE 6/ 1/1984
TEMPERATURE AMBIENT
FACILITY USED GILMORE
FILE Do0537

REFERENCE UNITS PSIA	TOTAL RAW OUTPUT RDC	TRANSDUCER OUTPUT RDG /PSIA	PERCENT DEVIATION FULLSCALE	PERCENT DEVIATION BEST FIT LINE
112.1	112.10	1.00036	.13	.57
212.1	211.90	.99925	.19	.46
312.1	311.10	.99692	.14	.23
412.1	410.00	.99500	.03	.04
512.1	$09.20	. .99246	-.22	-.22

****
* SENSITIVITY = .9946253 RDG /PSIA
****

BEST FIT STRRIGHT LINE SENSITIVITY EOURTIONS:
RDC • .99463 • PSIR
PSIA= 1.00540 • RDC

ZERO OFFSET 0.000 RDG
AMPLIFIER SUPPLY VOLTAGE 117. VRC

COMMENTS:
ZERO ADJUSTED AS REOUIRED. SPAN RS RECEIVED FROM
RLL INSTRUMENTS AND REFERNECES USED IN CALIBRATION
ARE TRACEABLE TO THE NRTIONRL BUREAU OF STIRNDARDS.

TRRNSDUCER CALIBRATION REPORT
SANDIA LABS 7546 11/14/1983

MANUFACTURER PRECISE SENSOR
MODEL 6540-1000-R-B
SERIAL 21293/CH 4
TRANSDUCER TYPE TRANSDUCER RND AMPLIFER SYSTEM
CERTIFIED BY WH
EXPIRATION DATE 6/ 1/1984
TEMPERATURE AMBIENT
FACILITY USED GILMORE
FILE DOD939

REFERENCE UNITS PSIA	TOTAL RAW OUTPUT RDC	TRRNSDUCER OUTPUT RDC /PSIA	PERCENT DEVIATION FULLSCALE	PERCENT DEVIRTION BEST FIT LINE
ii2.c	112.00	.99946	.02	.22
212.1	211.90	.99925	.04	.20
312.1	311.60	.99853	.04	.13
412.1	411.20	.99791	.03	.06
512.1	510.90	.99754	.01	.03
612.1	610.50	.99745	.01	.02
712.1	710.70	.99809	.06	.08
812.1	910.00	.99746	.02	.02
912.1	909.10	.99675	-.05	-.05
1012.1	1006.70	.99668	-.06	-.06

****
* SENSITIVITY = .9972690 RDG /PSIA
****

BEST FIT STRAIGHT LINE SENSITIVITY EOURTIONS:
RDC • .99727 • PSIA
PSIA= 1.00274 * RDC

ZERO OFFSET 0.000 RDC
AMPLIFIER SUPPLY VOLTAGE 117. VAC

Exhlblt B

TRANSDUCER CALI BRATION REPORT
SANDIA LABS 7146 11/14/1983

MANUFACTURER PRECISE SENSOR
MODEL 6540-1500-A-B
SERIAL 21293/CH 5
TRANSDUCER TYPE TRANSDUCER RND RMPLIFER SYSTEM
CERTIFIED BY WH
EXPIRATION DATE 6/1/1984
TERPERRTURE AMBIENT
FACILITY USED GILMORE
FILE D0054 1

REFERENCE UNITS PSIA	TOTAL RAW OUTPUT RDG	TRRNSDUCER OUTPUT RDC /PSIA	PERCENT DEVIATION FULLSCALE	PERCENT DEVIATION BEST FIT LINE
112.1	112.60	1 . 00482	.03	.34
212.1	212.80	1.00349	.03	.21
312.1	313.10	1.00333	.04	.19
412.1	413.20	1.00277	.04	.13
512.1	513.30	1.00242	.03	.10
612.1	613.40	1.00219	.03	.08
712.1	713.00	1.00244	.05	.10
012.1	813.60	1.00190	.03	.05
912.1	913.20	1.00129	-.01	-.02
1012.1	1013.70	1.00162	.01	.02
1112.1	1114.50	1.00219	.06	.08
1212.1	1213.60	1.00127	-.01	-.02
1312.1	1314.20	1.00163	.02	.02
1412.1	1413.10	1.00074	-.06	-.07
1512.1	1513.10	1.00069	-.07	-.07

******************************a***********
* SENSITIVITY . 1.0014250 RDC /PSIA
•

BEST FIT STRAIGHT LINE SENSITIVITY EQUATIONS:
RDG . 1.00142 * PSIR
PSIA= .99858 * RDG

ZERO OFFSET 0.000 RDG
AMPLIFIER SUPPLY VOLTAGE 117. VRC

COMMENTS:
ZERO RDJUSTED AS REQUIRED. SPAN AS RECEIVED FROM
ALL INSTRUMENTS AND REFERNECES USED IN CALIBRATION
ARE TRACEABLE TO THE NRTIONRL BUREAU OF STANDARDS.

Serial Nos. 21293, 21287, and 21299 system was installed in March 1984 (Day 0); the system failed January 1985 (Day 314).

Exhibit C

Pressure hysteresis test of Precise Sensor Transducer and transducer and amplifier system. Data recorded at constant tempature.

Modal 6540-500-A-B Serial 21293/Ch 3

Precise Sensor Indicator reading on front panel

psia input	increasing pressure	decreasing pressure	increasing pressure	final zero reading
e	0.0	8.6	8.6	0.5
100	98.8	188.8	99.2	
288	197.7	198.9	197.9	
300	296.2	297.7	296.4	
400	394.9	395.7	394.9	
500	492.7.	492.7	493.1	

Model 6548-1008-A-B Serial 21287/Ch 4

psia input	increasing pressure	decreasing pressure	increasing pressure	final zero reading
8	8.8	8.2	0.2	8.1
180	98.8	99.2	98.8	
288	197.6	198.1	197.5	
388	296.6	297.1	296.5	
408	395.8	396.2	395.7	
588	495.2	495.2	495.1	

Model 6540-1500-A-B Serial 21299/Ch 5

psia input	increasing pressure	decreasing pressure	increasing pressure	final zero reading
e	0.0	0.0	8.8	- 0.5
188	99.7	99.7	99.6	
288	199.3	199.6	199.3	
388	299.4	299.5	299.3	
488	399.4	399.7	399.2	
588	499.8	499.8	499.4	

Exhibit D

Pressure stability over time with a constant tempature
Constant standard input of 200 psia

Time	Transducer		
	Ch 3 500	Ch 4 1000	Ch 5 1500
8:00 am	199.7	199.2	199.9
9:00 am	200.1	199.2	199.3
10:00 am	200.1	199.2	199.1
11:00 am	200.1	199.1	199.9
12:15 pm	200.0	199.9	190.7
1:00 pm	200.0	199.0	190.7
2:00 pm	200.0	199.0	199.6
	1.0	- 0.2	- 1.2 final zero

Pressure stability over time uith a variable tempature
Constant standard input of 200 □·ӿ •

All channels were set to 9.0 before the temperature test.
Temperature was monitored on the body of the transducer.

Temp.	Ch 3 500 psia	Ch 4 1000 psia	Ch 5 1500 psia
se.2	199.4	197.7	197.8 temp. stable for 30 nin
100.0	196.6	197.9	260.3 temp. stable for 30 min
121.0	199.0	195.6	198.1 temp. stable for 30 rin
	- 2.6	- 5.4	- 2.7 final zero

Exhibit E

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7545 1/29/1985

MANUFACTURER PRECISE-SENSOR
MODEL 6540-500-A-B10
SERIAL 21288 DATAFILE # 1
TRANSDUCER TYPE DIAL GAGE
CERTIFIED BY WL EXPIRATION DATE 8/ 1/1985
TEMPERATURE AMBIENT FACILITY USED KIN6
COMMENTS: S. WALLACE, 6257: VALID ONLY WITH 453-FR-01-03,
S/N DPI 818, CHAN 4
CAL = 440.0 ● 12-1/84

REFERENCE UNITS PSIA	DIAL GAGE READING	% DEVIATION FULLSCALE
.5000E+02	50.20	.040
.1000E+03	100.50	.100
.1500E+03	151.00	.200
.2000E+03	201.30	.260
.2500E+03	251.40	.280
.3000E+03	301.30	.260
.3500E+03	351.40	.280
.4000E+03	401.00	.200
.4500E+03	450.70	.140
.5000E+03	500.20	.040

COMMENTS :
S. WALLACE, 6257: VALID ONLY WITH 453-FR-01-03,
S/N DPI 818, CHAN 4
CAL = 440.0
ALL INSTRUMENTS AND REFERENCES USED IN CALIBRATION
ARE TRACEABLE TO THE NATIONAL BUREAU OF STANDARDS.

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7545 1/29/1985

MANUFACTURER PRECISE-SENSOR
MODEL 6540-1000-A-B10
SERIAL 21282 DATAFILE # ● 1
TRANSDUCER TYPE DIAL GAGE
CERTIFIED BY WL EXPIRATION DATE 8/ 1/1985
TEMPERATURE AMBIENT FACILITY USED KIN6
COMMENTS: S. WALLACE, 6257: VALID ONLY WITH 453-FR-01-03,
S/N DPI 818, CHAN 5
CAL = 731.2 ● 12.0 PSIA

REFERENCE UNITS PSIA	DIAL GAGE READING	% DEVIATION FULLSCALE
.1000E+03	160.30	.030
.2000E+03	200.80	.080
.3000E+03	301.00	.100
.4000E+03	401.00	.100
.5000E+03	581.20	.120
.6000E+03	601.00	.100
.7000E+03	700.80	.080
.8000E+03	800.90	.090
.9000E+03	900.50	.050
.1000E+04	1000.20	.020

ALL INSTRUMENTS AND REFERENCES USED IN CALIBRATION
ARE TRACEABLE TO THE NATIONAL BUREAU OF STANDARDS.

Exhlblt F

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7545 1/29/1985

MANUFACTURER PRECISE-SENSOR
MODEL 6540-1500-A-810
SERIAL 21294 DATAFILE # 1
TRANSDUCER TYPE DIAL 6 6E
CERTIFIED BY WL~~ 3 EXPIRATION DATE 8/ 1/1985
TEMPERATURE AMBIENT FACILITY USED KING
COMMENTS: 5. WALLACE, 6257: VALID ONLY WITH 453-FR-01-03,
S/N DPI 818, CHAN 6
CAL-1260.8 @ 12.0 PSIA

REFERENCE UNITS PSIA	DIAL 6AGE READING	% DEVIATION FULLSCALE
.1500E+03	150.90	.060
.3000E+03	301.40	,093
.4500E+03	451.40	.093
.6000E+03	601.50	.100
.7500E+03	751.60	.107
.9000E+03	901.30	.087
.1050E+04	1051.20	.080
.1200E+04	1201.50	.100
.1350E+04	1351.20	.080
.1500E+04	1501.00	.067

ALL INSTRUMENTS AN0 REFERENCES USED IN CALIBRATION
ARE TRACEABLE TO THE NATIONAL BUREAU OF STANDARDS.

Serial Nos. 21288, 21282, and 21294 system was installed in February 1985 (Day 349); the system was removed at the end of the test.

Exhlblt G

TRANSDUCER CALIBRATION REPORT
SRNDIA LABS 7546 3/22/1 9 0 4

DATAFILE # DO0340

MANUFACTURER VIATRAN CH 7
MODEL 104
SERIAL 050699N3
TRANSDUCER TYPE METAL STRAIN GAGE
CERTIFIED BY WL
EXPIRATION DATE 10/ 1/1984
FACILITY USED RUSKA

REFERENCE UNITS PSIA	TOTAL RAW OUTPUT MV	TRANSDUCER OUTPUT MV/V/PSIA	PERCENT DEVIATION FULLSCALE	PERCENT DEVIATION BEST FIT LINE
50.0	2.54	.00500	.00	.03
100.0	5.05	.00500	.02	.09
150.0	7.55	.00500	.03	.08
200.0	10.05	.00500	.04	.09
250.0	12.55	.00500	.04	.07
250.0	12.57	.00501	.12	.23
3 0 0 . 0	15.05	.00500	.03	.05
350.0	17.55	.00500	.02	.03
400.0	20.04	.00500	-.00	-.00
450.0	22.53	.00500	-.04	-.05
500.0	25.02	.00500	-.09	-.09

************* SENSITIVITY = .0050004 MV/V/PSIA************

BEST FIT STRAIGHT LINE SENSITIVITY EQUATIONS:
PSIA= (199.9821 . MV)/EXCITATION VOLTAGE
MV= (.0050 . PSIA)=EXCITATION VOLTAGE
RESISTANCE(OHMS) I N P U T - 350.0 OUTPUT=350.0 INSULATION- >10MEG
ZERO OFFSET .04 MV
RECOMMENDED EXCITATION 10.0 VOLT

PSIA = CH 7 • 'J * (1+.7/350)/(.0050004 • CH 6 V)

PSIA = CH 7 mV * (lead resistance/transducer bridge resistance)
devided by
(scale factor [mV/V/PSI] * CH 6 Volts)

DATAFILE # D00341

MANUFACTURER T/TABER CH 8
MODEL 2201
SERIAL 050699N3
TRANSDUCER TYPE METAL STRAIN GAGE
CERTIFIED BY WL
EXPIRATION DATE 10/ 1/1984
FACILITY USED RUSKA

REFERENCE UNITS PSIA	TOTAL RAW OUTPUT MV	TRANSDUCER OUTPUT MV/V/PSIA	PERCENT DEVIATION FULLSCALE	PERCENT DEVIATION BEST' FIT LINE
20.0	3.02	.01506	.07	.67
40.0	6.02	.01505	.12	.58
60.0	9.02	.01503	.15	.49
80.0	12.02	.01502	.16	.39
100.0	15.01	.01500	.14	.29
100.0	15.02	.01501	.18	.35
120.0	17.99	.01499	.11	.19
140.0	20.97	.01497	.06	.08
160.0		.01495	-.03	-.03
180.0	E-8993	.01494	-.14	-.15
200.0	29.84	.01492	-.27	-.27

************* SENSITIVITY = .0149598 MV/V/PSIA************

BEST FIT STRAIGHT LINE SENSITIVITY EQUATIONS:
PSIA- (66.8460 • MV)/EXCITATION VOLTAGE
MV= (.0150 • PSIA)=EXCITATION VOLTAGE
RESISTANCE(OHMS) INPUT- 285.0 OUTPUT= 285.0 INSULATION= >10MEG
ZERO OFFSET .004 MV
RECOMMENDED EXCITATION 10.0 VOLT

PSIA = CH 8 • (1+.7/285)/(.0149598 • CH 6 V)

PSIA = CH 8 mV * (lead resistance/transducer bridge resistance)
devided by
(scale factor [mV/V/PSI] * CH 6 Volts)

Exhibit H

PRIMARY STANDARDS LABORATORY
SANDIA NATIONAL LABORATORIES
ALBUQUERQUE , NH 87185

CERTIFICATE

FILE NUMBER 30008

FLOWMETER
MANUFACTURER HALLIBURTON
MODEL NUMBER 85982
SERIAL NUMBER 2ST9876

SUBMITTED BY SNLA DIV 6257

CERTIFIED NOVEMBER 29, 1983
EXPIRES NOVEMBER 30. 1984

CALIBRATION FLUID DEIONIZED WATER
VISCOSITY IN CENTIPOISE .879551 • 25.7 DEG C
VOLUME DISPLACEMENT(D)= 5.01634 GALLONS

NRTZ = C/B
GPM =60D/A
K = CA/DB

TEST RESULTS

A* SECONDS	B** SECONDS	C PULSES	HERTZ	FLOW GAL/MIN	K PULSES/GAL	T TEMP of water °C
5.201	5.20345	214	41.1	57.87	43	25.7
3.42973	3.42642	212	61.9	87.756	42	25.7
2.56578	2.56506	212	82.6	117.306	42	25.8
2.03661	2.03752	213	104.5	147.785	42	25.8
1.49533	1.69557	213	125.6	177.535	42	25.9
1.44753	1.44667	213	147.2	207.927	42	26
1.44546	1.44725	214	147.9	208.225	43	18.1
1.44692	1.44793	214	147.8	208.015	43	37.6
1.43689	1.4355	214	149.1	209.467	43	65

*A- VOLUME DISPLACEMENT TIME - time It takes to displace 5.01634 gal
**B- EXACT TIME PERIOD FOR C PULSES

THE UNCERTAINTY IN REPORTED PULSES PER GALLON IS ESTIMATED TO BE NO GREATER THAN 2.0%.

The flowmeter was monitored using the Rallibruton flw analyzer model number HP-l, serial number 1006729 with the proper switches set internally to yield a readout in gallons per minute.

The flowmeter was tested with deionized water flowed into a 5.00 gallon collection &vice over the range of flow rates and temperatures shown below:

Temp °F	Time Sec	Total Counts	Plow GPM	A Pulse/gal	Ralliburton GPM/AVERAGE
65	1.45	214		42.8	204.5
75	5.2	212	207.5 57.68	42.8	57.0
75	3.43	212	116.92 87.47	42.4	86.0
75	2.56	21		42.4	115.5
75	2.04	213	147.3	42.6	143.8
75	1.7	213		42.6	173.5
75	1.45	213	176.9 207.25	42.6	205.7
100	1.45	214	208.78 207.34	42.8	204.7
150	1.44	214		42.8	205.1

The standard used was the flow technology ballistic flow prover model number BFP-1000-12-3-150, serial number BFP-002.

Exhibit I

TRANSDUCER CALIBRATION REPORT
SANOIA LABS 7545 9/ 3/1985

MANUFACTURER PRECISE-SENSOR
MODEL 6540-500-A-B10
SERIAL 21288 OATAFILE # 3
TRANSDUCER TYPE DIAL GAGE
CERTIFIED BY OS EXPIRATION DATE 4/ 1/1986
TEMPERATURE AMB IENT FACILITY USED RUSKA
COMMENTS: S. UALLACE, 6257: CAL CH4= 419.1 PSI AT 0.0
PSI6 (12 PSIA), VALID WITH AMP SN OPI-818
READ FROM DIAL SAGE

REFERENCE UNITS PSIG	DIAL GAGE READING	% DEVIATION FULLSCALE
.5000E+02	49.10	-.184
15001000E+03	147.30 98.20	-.369 -.553
.2000E+03	196.40	-.738
.2500E+03	245.40	-.943
.3000E+03	294.20	-1.189
.3500E+03	342.90	-1.455
.4000E+03	391.40	-1.762
.4500E+03	439.80	-2.090
.5000E+03	48B.00	-2.459

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TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7545 8/30/1985

MANUFACTURER PRECISE-SENSOR
MODEL 6540-1000-A-B10
SERIAL 21282 DATAFILE # 3
TRANSDUCER TYPE DIAL GAGE
CERTIFIED BY O S EXPIRATION DATE 3/ 1/1986
TEMPERATURE AMBIENT FACILITY USED GILMORE
COMMENTS: S. WALLACE,6257: CAL CH5 716.3 PSI AT 0.0 PSIG
(12 PSIA) VALID WITH AMP SN OPI-818
READ FROM DIAL GAGE

REFERENCE UNITS PSIG	DIAL GAGE READING	% DEVIATION FULLSCALE
.1000E+03	100.60	.060
.2000E+03	201.20	.120
.3000E+03	301.60	.160
.4000E+03	401.80	.180
.5000E+03	502.10	.209
.6000E+03	602.40 .23	9
.7000E+03	702 .60	.253
.8000E+03	802.70	.269
.9000E+03	902.70	.269
.1000E+04	1002.70	.269

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Post test calibration

Exhibit J

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7545 8/30/1985

MANUFACTURER	PRECISE-SENSOR		
MODEL	6540-1516-G-810		
SERIAL	21294	DATAFILE # 3	
TRANSDUCER TYPE	DIAL GAGE		
CERTIFIED BY	DS	EXPIRATION DATE 3/1/1986	
TEMPERATURE	AMBIENT	FACILITY USED	GILMCRE
COMMENTS:	S.WALLACE,6257: CAL CH6= 1223.8 PSI AT 0.0 PSIG (12 PSIA), VALID WITH AMP SN DPI-818 READ FROM DIAL GAGE		

REFERENCE UNITS PSIG	DIAL GAGE READING	% DEVIATION FULLSCALE
.1500E+03	ib8.73	-.088
.3000E+03	236.70	-.223
.4500E+03	444.50	-.372
.6000E+03	532.50	-.507
.7500E+03	740.20	-.662
.9000E+03	888.10	-.804
.1050E+04	1336.33	-.926
.1200E+04	1184.20	-1.063
.1350E+04	1332.00	-1.216
.1500E+04	1479.90	-1.358

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TRANSDUCER CALIBRATION REPORT
SGNDIG LABS 7545 9/ 3/1985

MANUFACTURER	TELEDYNE -TABER	
MODEL	2201	
SERIAL	841703	DATAFILE # 2
TRANSDUCER TYPE	METAL STRAIN GAGE	
CERTIFIED BY	DS	EXPIRATION DATE 4/1/1986
TEMPERATURE	AMBIENT	FACILITY USED RUSKA
COMMENTS :	S. WALLACE. 6257	

REFERENCE UNITS PSIA	TOTAL RAW OUTPUT MV	TRANSDUCER OUTPUT MV/V/PSIA	PERCENT DEVIATION FULLSCALE	PERCENT DEVIATION BEST FIT LINE
20.0	3.45	.01503	.08	-.85
40.0	6.46	.01504	.17	-.87
60.0	3.45	.01501	.21	-.71
80.0	12.42	.01497	.17	-.42
100.0	15.41	.01496	.19	-.56
120.0	18.38	.01495	.17	-.28
140.0	21.34	.01493	.11	-.16
160.0	24.27	.01489	-.06	.07
180.0	27.21	.01487	-.19	.21
203.0	30.18	.01487	-.23	.23

************* SENSITIVITY = .0149056 MV/V/PSIA*************

BEST FIT STRAIGHT LINE SENSITIVITY EQUATIONS:
PSIA=(67.0830 • MV)/EXCITATION VOLTAGE
NV=(.0149 • PSIA)*EXCITATION VOLTAGE
RESISTANCE(OHMS) INPUT= 343.0 OUTPUT= 351.0 INSULATION= >10MEG
TEST EXCITATION 10.0 VOLT
ZERO: .44600 NV TREATED A5 OFFSET

Post test calibration

APPENDIX B

Finite Element Calculations

Finite Element Computer Program

SANCHO is a finite element structural computer program developed from HONDO II' specifically for calculating the creep closure of underground cavities in rock salt.' Uses of the program to date are documented in References 3 through 8. SANCHO is a large-strain, large-deformation program containing a variety of constitutive models. The solution strategy is based on dynamic relaxation wherein an acceleration term is added to the equilibrium equation converting the static problem into a dynamic one in pseudo time. An instantaneously optimum damping value is computed internally at each time step and is used to follow the transient response in pseudo time until a converged solution is obtained. Satisfaction of global equilibrium at each load step is used to control the convergence of the iterative procedure. The magnitudes of the residual-force vector and the applied-load vector are compared to determine when global equilibrium has been reached.

The material model for creep currently is secondary creep expressed in power-law form. The creep model is integrated semianalytically, which proves to be accurate for any strain step size. This method has no stability or time step restrictions usually associated with classical Euler integration. The only restriction is that the strain rate should be approximately constant during the time step.

Material Properties

To our knowledge, salt core from the Sulphur Mines site has never been laboratory tested for elastic or creep material properties. There exist, however, a significant amount of laboratory test data from the West Hackberry and Bryan Mound SPR sites. Even though salt-creep properties vary from site to site, the variance from one site to another is usually within the data scatter at any particular site.[9] Extensive triaxial creep testing of West Hackberry core has produced the credible creep model"' used in this study.

In this study the finite element program SANCHO used a secondary creep model of the form

$$\bar{e} = A \exp(-Q/RT)(S)^n \qquad (1)$$

where

$\bar{e}$ = secondary effective creep strain rate
A = laboratory-determined constant
Q = activation energy
R = universal gas constant
T = temperature in degrees Kelvin
s = effective stress or Von Mises stress
n = stress exponent.

The above parameters that were input to the computer program are given below."'

A = 3.037×10^{-21} $1/[(\text{day})(\text{psf})]^n$
Q = 13120 [Cal/mole K]
n = 4.73
R = 1.986 cal/mole K
T = 326.33 K.

As can be seen in the equation above, salt creep is dependent on temperature. The in situ temperature around Sulphur Mines 6 is not known exactly, but is estimated from temperature logs of the Big Hill site to be ~128°F at a depth of 3500 ft. The actual temperature distribution around the cavern varies in both space and time, but accurate information about the temperature distribution does not exist. The finite element analyses were performed by assuming a constant temperature of 128°F across the mesh and throughout the time of the analyses. This approach was also taken for the analyses of other caverns in the SPR." The elastic properties were obtained from quasi-static test data on Weeks Island, West Hackberry, and Bryan Mound core[11,12] and are as follows:

Young's Modulus = 6.38×10^8 psf

Poisson's Ratio = 0.30.

Finite Element Analyses

In Figure 2 (main body of this report), cavern 6 has several ledges that sonar logs show to be approximately axisymmetric. A finite element analysis of cavern 6 was done primarily for two purposes: The first was to determine the influence of the ledged shape on the creep closure of the cavern and how field data from this cavern should compare with field data from other caverns that have a cylindrical (ledge-free) shape. The second was to compare the finite element-calculated creep closure with the field data from this cavern to determine how well the finite element program plus the material model is performing and the validity of the simplified geometry and temperature distributions.

The first objective was accomplished by creating three finite element models of this cavern. The first, shown in Figure B1, had the same depth and axial length as the actual cavern. It also approximately modeled the ledges in the cavern and had the same total volume (7 MMBBL). The second model had the same depth, axial length, and total volume as the actual cavern but was cylindrical, with no ledges, and consequently had a smaller radius. This model is shown in Figure B2. The third model also had the same depth and axial length as the other two, but the radius was made the same as the maximum radius of the ledged model (Figure B1) and consequently had a larger volume (12.13 MMBBL). This model is shown in Figure B3. The three models have similar boundary conditions, with a surcharge pressure on top corresponding to the in situ stress at that depth, fluid pressure inside the cavern based on brinehead to the surface of the ground, and body forces caused by gravity. The roller-displacement-constraint boundary conditions shown in the figures allow displacements parallel to the roller but not perpendicular to it.

The finite element formulation for creep, which incorporates the secondary creep model given above, allows calculation of the inward displacement of the cavern walls throughout analysis time. Computer programs have been written to process the cavern wall displacements into volume and pressure change vs time.[7] The volume change vs time is termed cavern flow rate and is given in barrels per day. Pressure change vs time is given in psi per day. Care must be taken in comparing the calculated pressure changes with field data because the field data pressure rise must be corrected for fluid thermal expansion, fluid compressibility, and salt compressibility. The field data must also be extrapolated from the wellhead working pressure at which they were measured down to zero wellhead pressure. Calculated and measured pressure change vs time, with the appropriate corrections made, are given in Table B1.

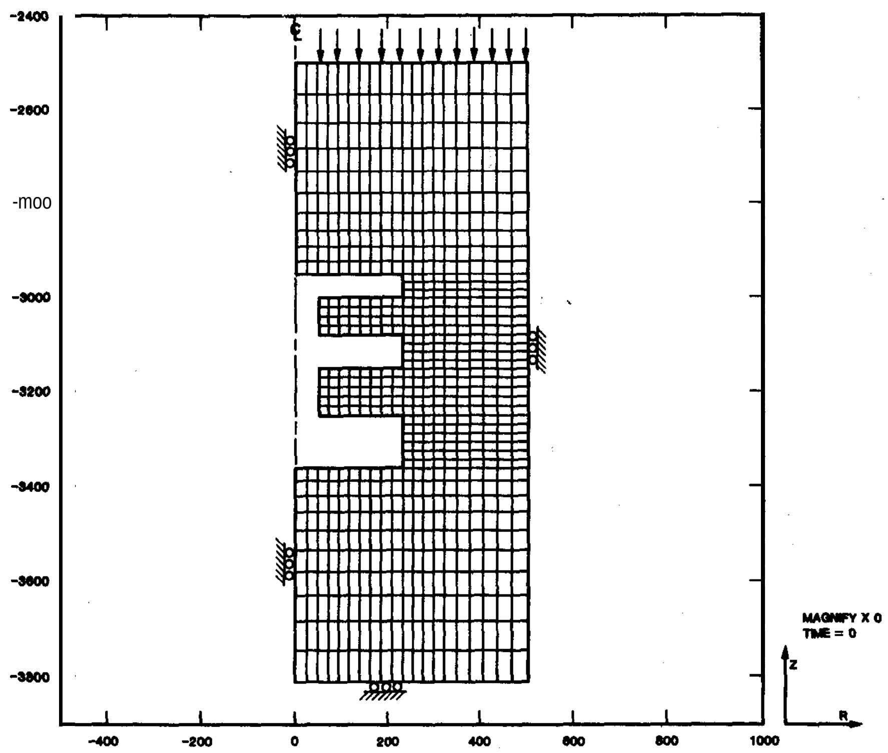

Figure B1. Sulphur Mines Cavern 6 With Ledges (230-ft radius)

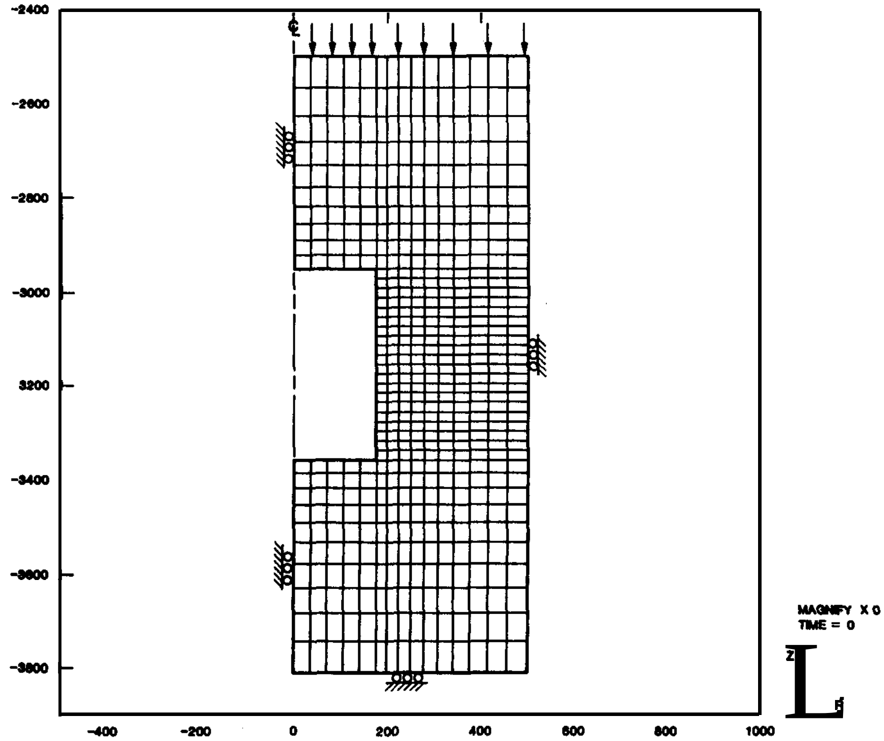

Figure B2. Sulphur Mines Cavern 6 Modeled as a Cylinder (175.42-ft radius)

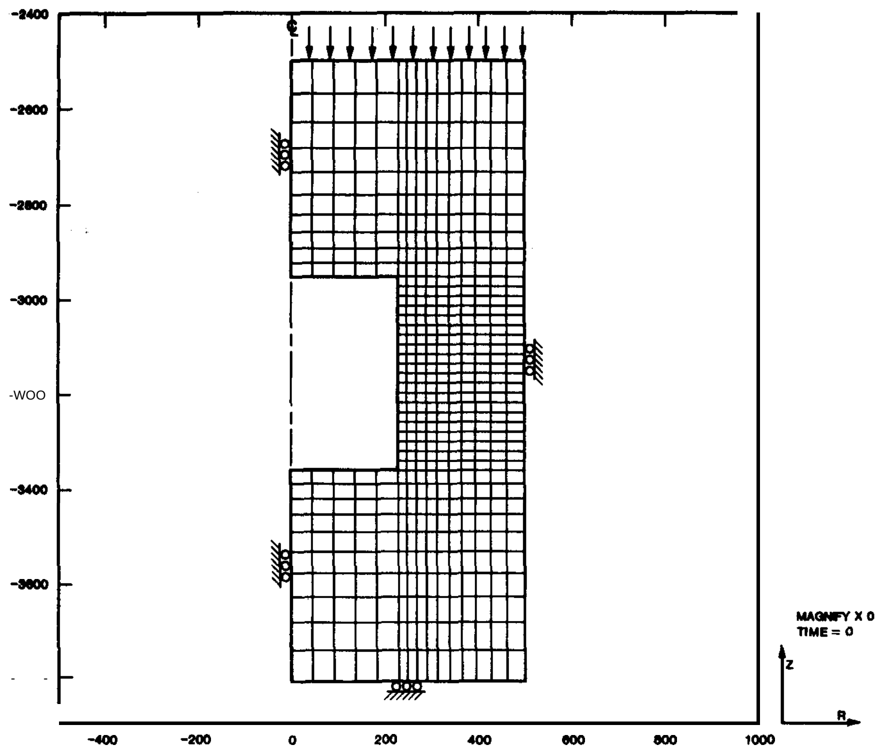

Figure B3. Sulphur Mines Cavern 6 Modeled as a Cylinder (230-ft radius)

Table B1. Comparison of Finite-Element Results and Field Data for Sulphur Mines 6 at 0 psi or Brinehead Pressure

Model	Radius (ft)	Volume (MMBBL)	Flow Rate (ft^3/day)	Flow Rate (bbl/day)	Pressure Change (psi/day)
Ledge	230	7	880	157	4.2
Cylindrical	175	7	632	112	3.1
Cylindrical	230	12.15	1787	318	8.6
Field Data					3.7

Examination of Table B1 can provide answers to the first objective of this study. It appears from this table that the ledges have a significant impact on the creep closure of the cavern. The ledged model experienced significantly less closure than the cylindrical cavern with the same maximum radius. In this case, the ledges stiffen the cavern similar to the manner in which ribs stiffen a pressure vessel. The ledged model experiences slightly more closure than the cylindrical cavern with the same volume. This is a trend that might be expected as field data from ledged caverns are compared with other caverns. The field data lie between the ledged cavern closure and the cylindrical same-volume cavern closure.

Contours of von Mises stress, which drives creep closure, are shown in Figure B4 for the ledged model and Figure B5 for the cylindrical model with the same volume. As can be seen from the creep model in Eq (1), creep strain rate, and consequently creep displacement, is a power-law function of von Mises stress. The magnitude and distribution of von Mises stress around the cavern, along with the creep model, determine the cavern closure. It is interesting to note that the von Mises stress envelope around the cavities, defined by the E contour, is in approximately the same place for both the ledge and cylindrical models even though the ledge model contour is more irregular. The D contour is also similar for both models. Similarity in magnitude and distribution of von Mises stress around both ledged and cylindrical models provides an explanation for the similarity in creep response.

Table B1 also addresses the second objective of the study. The field data listed in the table contain the contribution to pressure change due only to creep and is corrected for fluid thermal expansion and the difference in wellhead operating pressure. This value lies between the pressure rise calculated by the ledge model and cylindrical same-volume model, and indicates reasonable correlation between field data and finite element results.

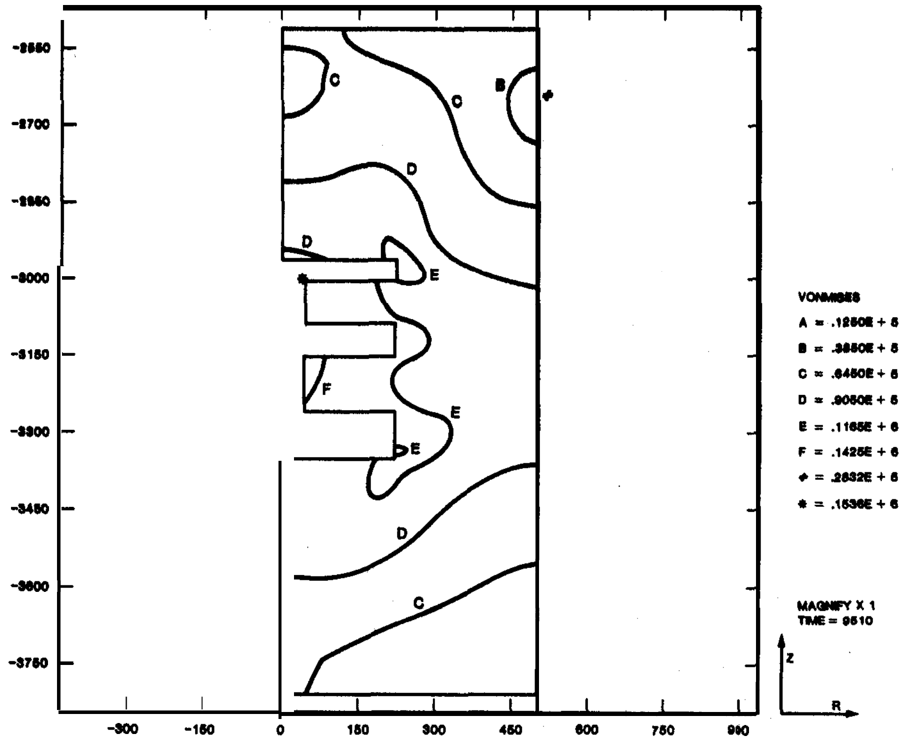

Figure B4. Sulphur Mines Cavern 6 With Ledges (230-ft radius)

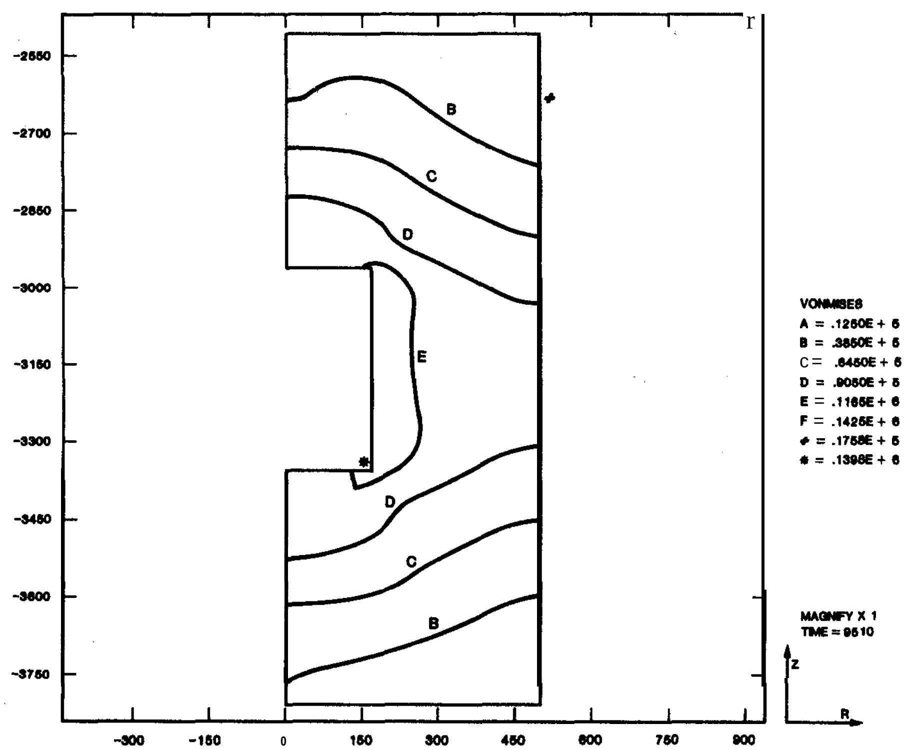

Figure B5. Sulphur Mines Cavern 6 Modeled as a Cylinder (175.42-ft radius)

Conclusions

It appears from these analyses that a ledged cavern with a larger maximum radius creeps slightly more than a cylindrical cavern with the same volume. The ledged cavern also creeps significantly less than a cylindrical cavern with the same maximum radius and a larger volume. This indicates that cavern volume is a dominant factor in creep response and that other things, such as radius, have a minor effect. The comparison of field data to finite element results is relatively good for this model, even with the simplifying assumptions made during the analyses.

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